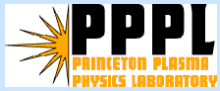


Heavy Ion Fusion

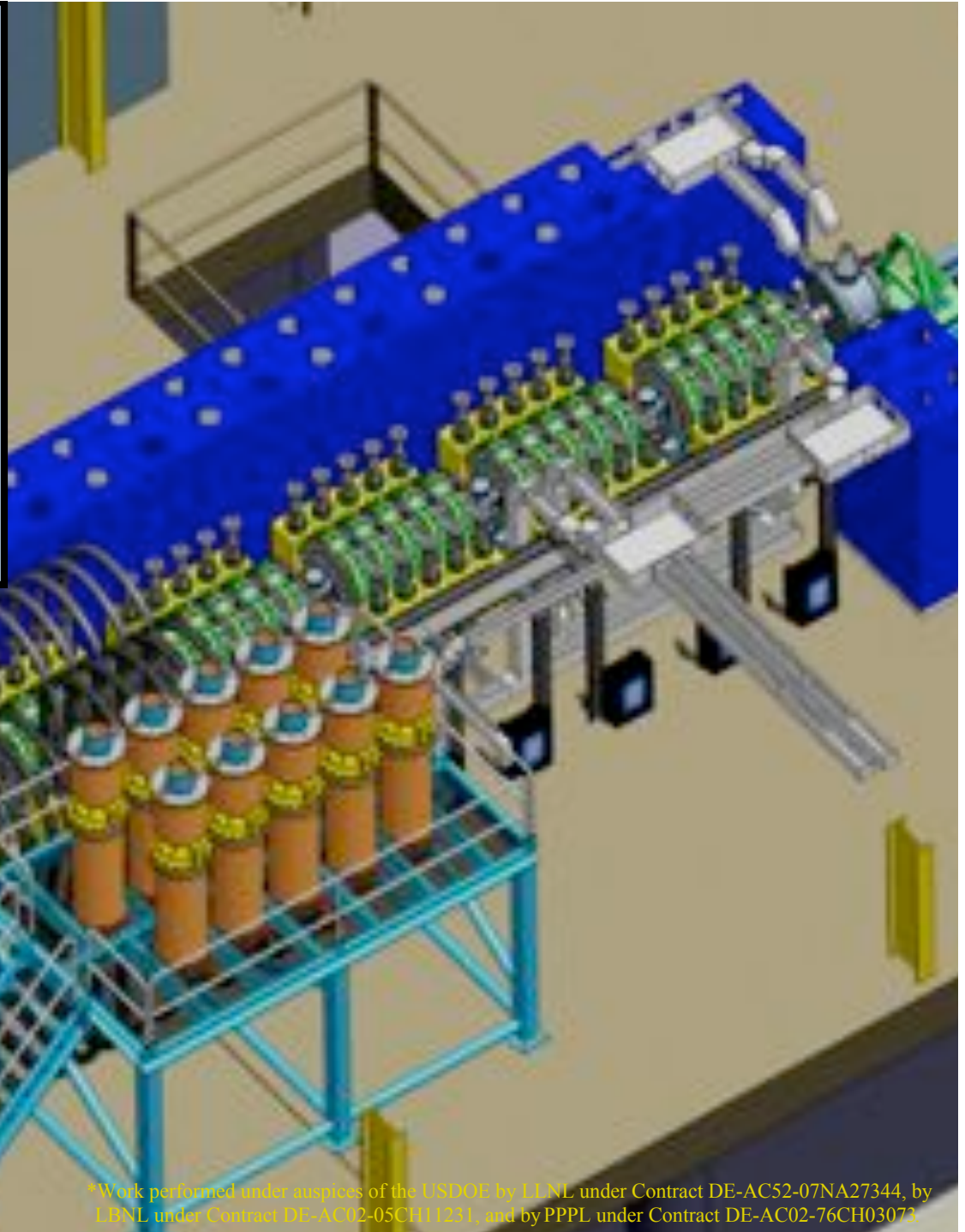
*An overview of the program
and its computational science**

Alex Friedman

Simulations and Theory Group Leader
HIF Science Virtual National Laboratory



Computational Engineering Science
Seminar, UC Berkeley, March 17, 2009



*Work performed under auspices of the USDOE by LLNL under Contract DE-AC52-07NA27344, by LLNL under Contract DE-AC02-05CH11231, and by PPPL under Contract DE-AC02-76CH03073.

Talk Outline

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How can we address energy and climate challenges?

- Population growth roll-off (education, economics, ...)
- Conservation (more efficient vehicles, buildings, appliances, ...)
- Innovation in industrial processes and materials
- Solar, wind, biofuels, ...
not concentrated, use lots of land
- Fission (nuclear power plants, A-bombs)
radioactive waste, proliferation
- How about Fusion (the sun and stars, H-bombs) ???

Fusion is (potentially) an attractive energy source

Supply:

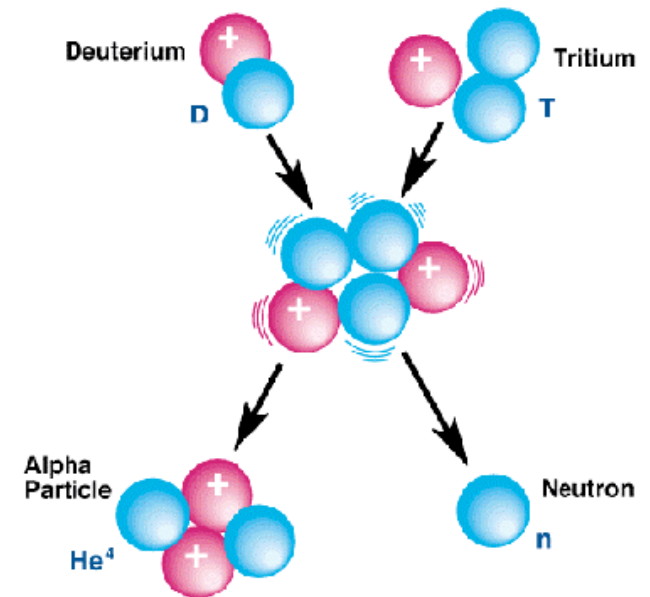
- Plentiful fuel

Environment:

- No CO₂ & no air pollution
- No radioactive waste from reaction
- Relatively short half-life for components

Safety:

- No weapons material produced
- Nuclear accidents impossible



Fusion energy requires plasma conditions

To fuse, nuclei must:

- Overcome electrostatic repulsion - requires energy (millions of degrees)
- Sufficient number and rate of interactions - requires many particles

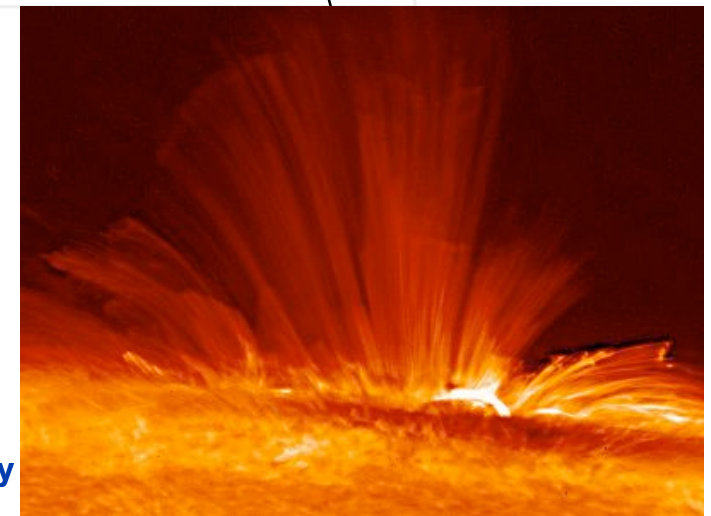
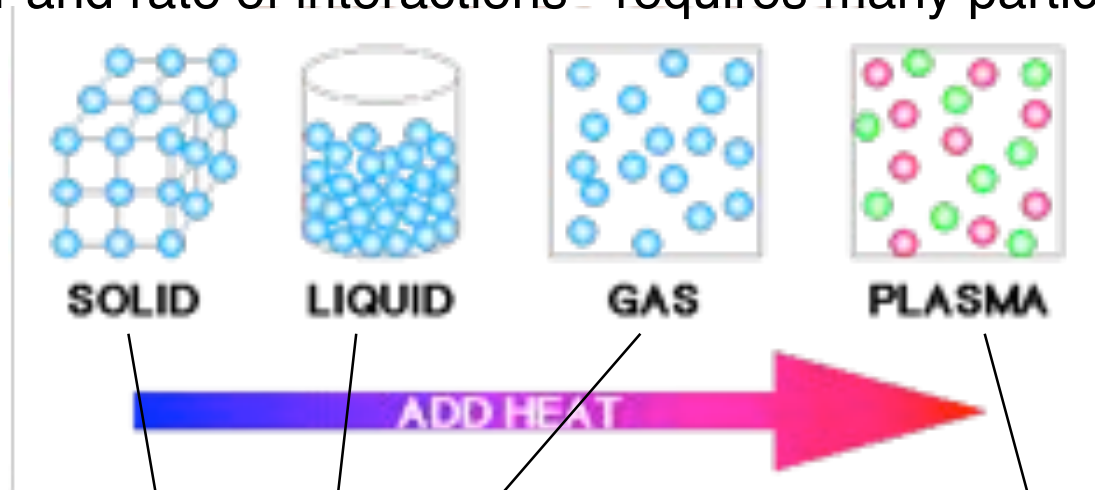
Lawson criterion:

$$n \tau > 10^{14} \text{ s/cm}^3$$

Temperature:

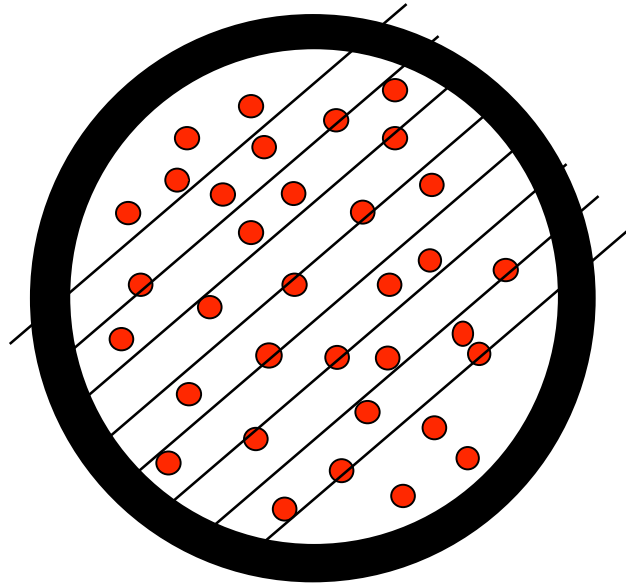
$$T > \sim 10 \text{ keV}$$

$$\sim 100 \text{ M } ^\circ\text{C}$$



Two Approaches to Fusion

Magnetic Confinement



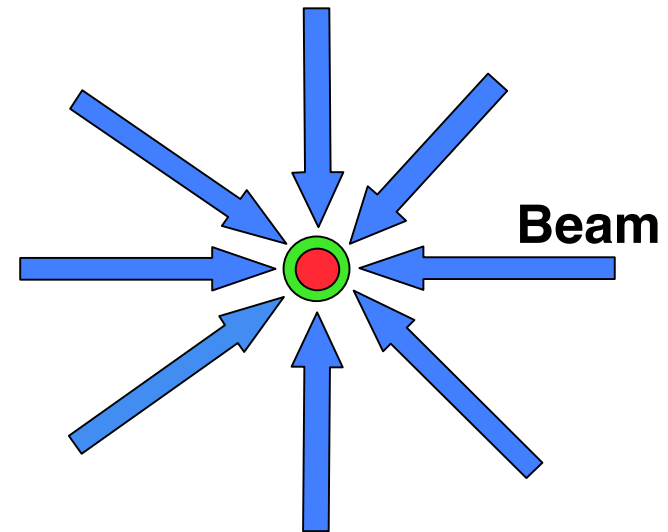
Fuel: D + T Gas

Cycle: constant, or few minutes

Meters in radius

$$n\tau T > 10^{15} \text{ keV-s/cm}^3$$

Inertial Confinement



Fuel: Solid D+T

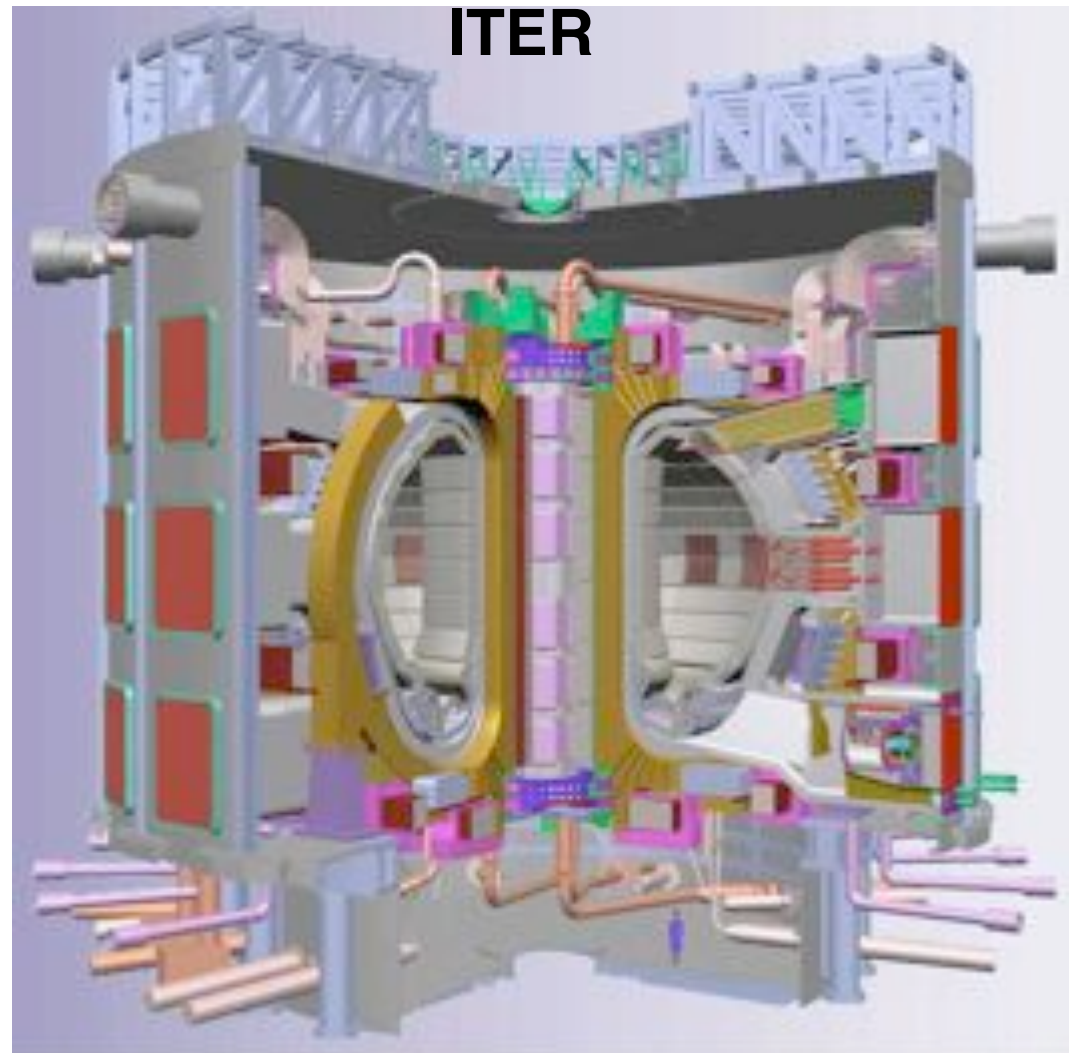
Cycle: 5 times per second

Few millimeters radius

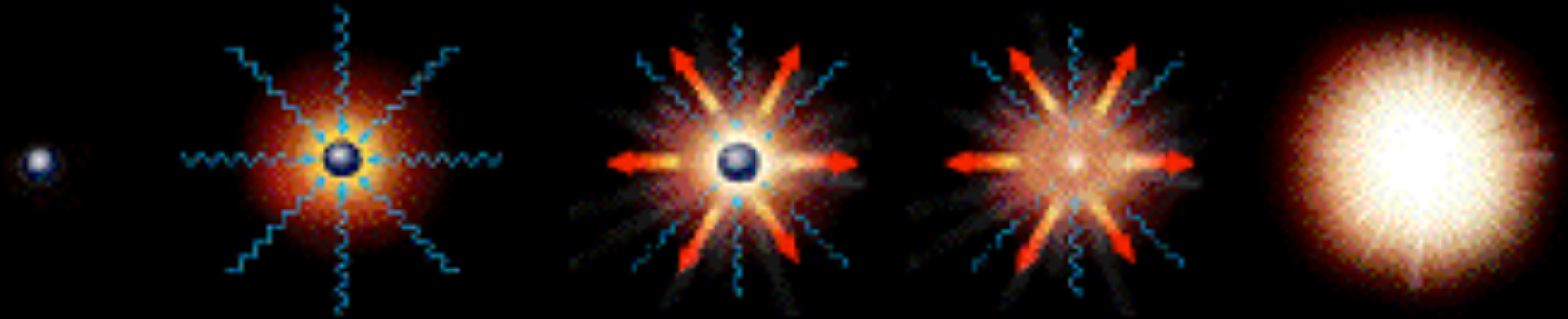
$$\rho R > 1 \text{ g/cm}^2$$

The world is exploring “magnetic fusion energy” (MFE)

- ~ \$250 M/year in US alone (far more worldwide)
- Plasma confinement is the main topic being studied
- Complicated system to maintain; driver, blanket, chamber not separable; “first wall” is exposed
- Short DT burn ~2020; full noninductive drive ~2023



Inertial Confinement Fusion Concept



Fuel Capsule

A small metal or plastic capsule (about the size of a pea) contains fusion fuel

Target Heating

Radiation (light, X-rays, ions, or electrons) rapidly heats the surface of the fuel capsule

Compression

Fuel is compressed (imploded) by rocket-like blowoff (ablation) of the surface material

Ignition

With the final driver pulse, the fuel core reaches about 1000 times liquid density and ignites at 100,000,000 degrees

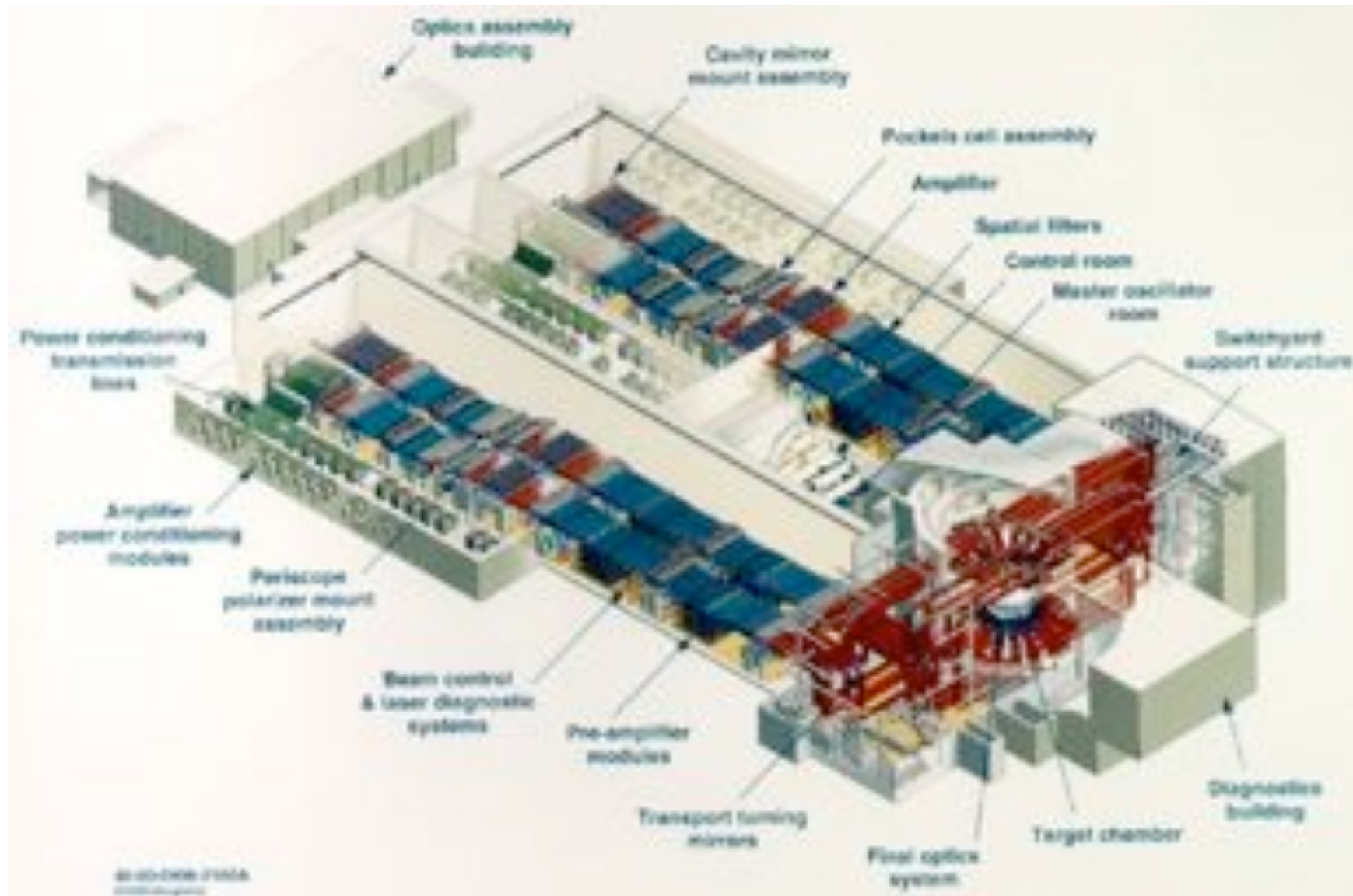
Burn

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy

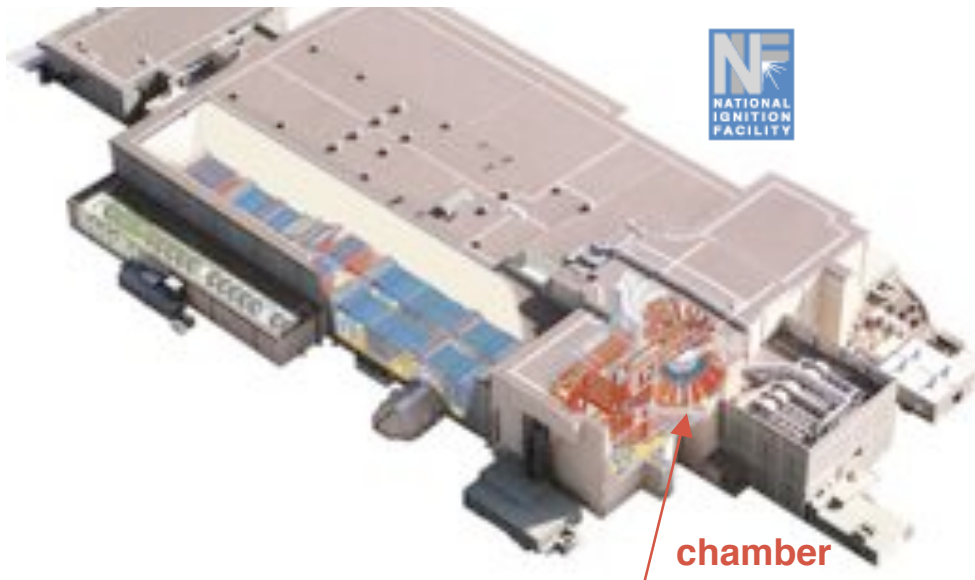


Blowoff Radiation

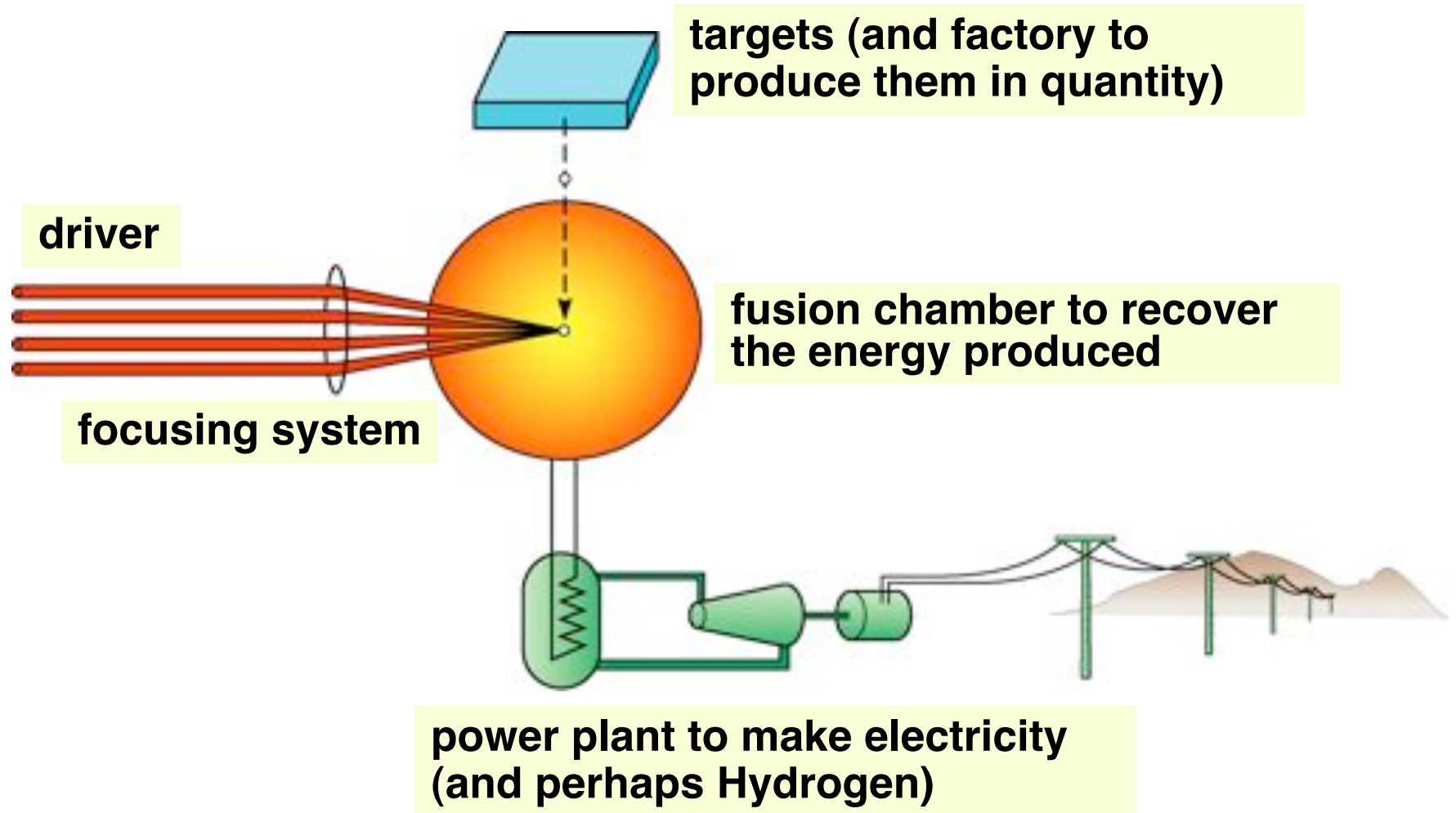
The National Ignition Facility at LLNL is scheduled to complete first “ignition campaign” by 2011



NIF and LMJ in France are of unprecedented scale



Inertial Fusion Energy (IFE) concepts are modular, and differ significantly from Magnetic Fusion Energy concepts



Lasers vs. Ions

Lasers:

Easy to focus

Much more money in program

Easier development path (beams don't interact)

but:

Problem protecting final optics

Problem protecting first wall

} All

Low repetition rate (a few/day)

Low electrical efficiency (a few - 10%)

} Glass lasers

Cost (DPSSL)

Lifetime (KrF)

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The HIF program's goal is an environmentally attractive and economical IFE power plant



Heavy ion accelerators are a good choice for an Inertial Fusion Energy driver

High Energy Physics accelerators already have:

Long life

High pulse repetition rates

High electrical efficiency (~ 30%)

Present systems comparable to requirements in:

complexity

cost

ion energy

If accelerators are so mature a technology, why is building a fusion driver challenging?

New physics regime for accelerators

Target Requirements:

500 Terawatts (but maybe less ...)

1- 10 GeV



$\sim 10^{16}$ ions

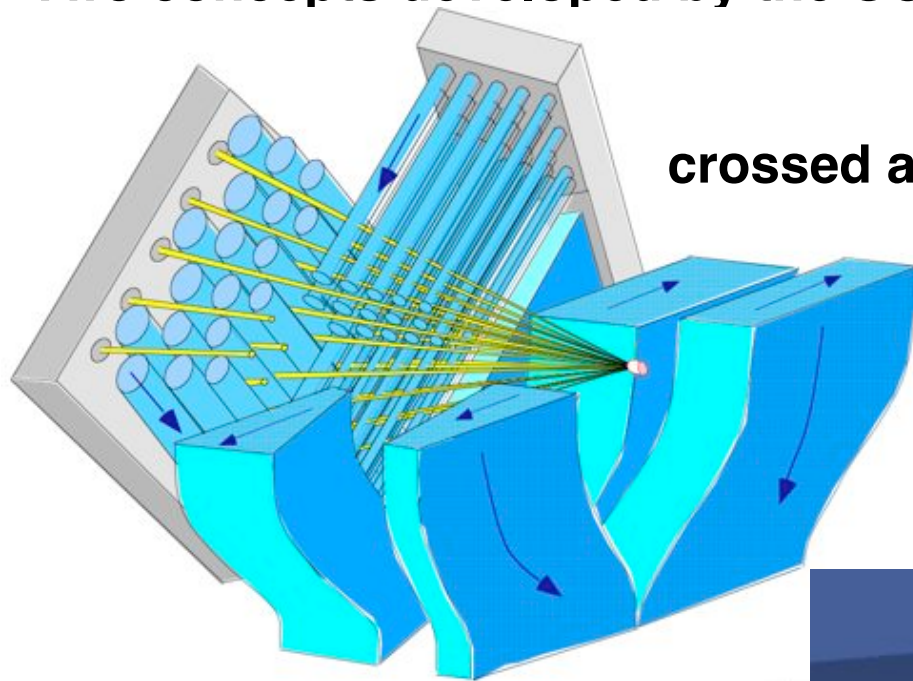
~ 100 beams

a million times more ions than
in conventional machines

Beam particles *interact* -- this dominates the physics.

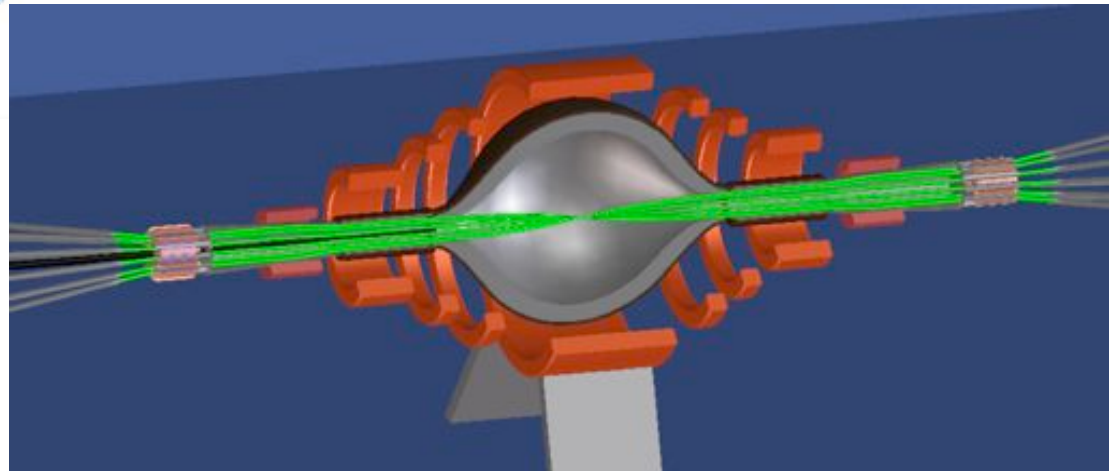
In most HIF concepts, the first wall is protected by neutronically-thick liquid, commonly FLiBe, a molten salt

Two concepts developed by the UC Berkeley group and its collaborators:

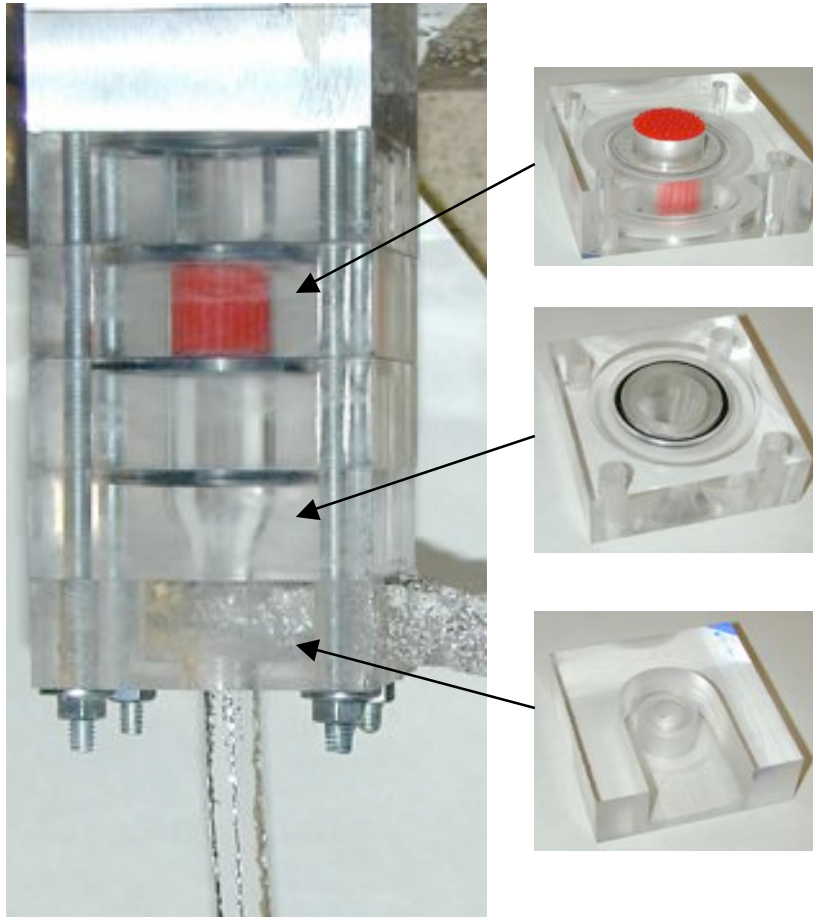


crossed and oscillating jets

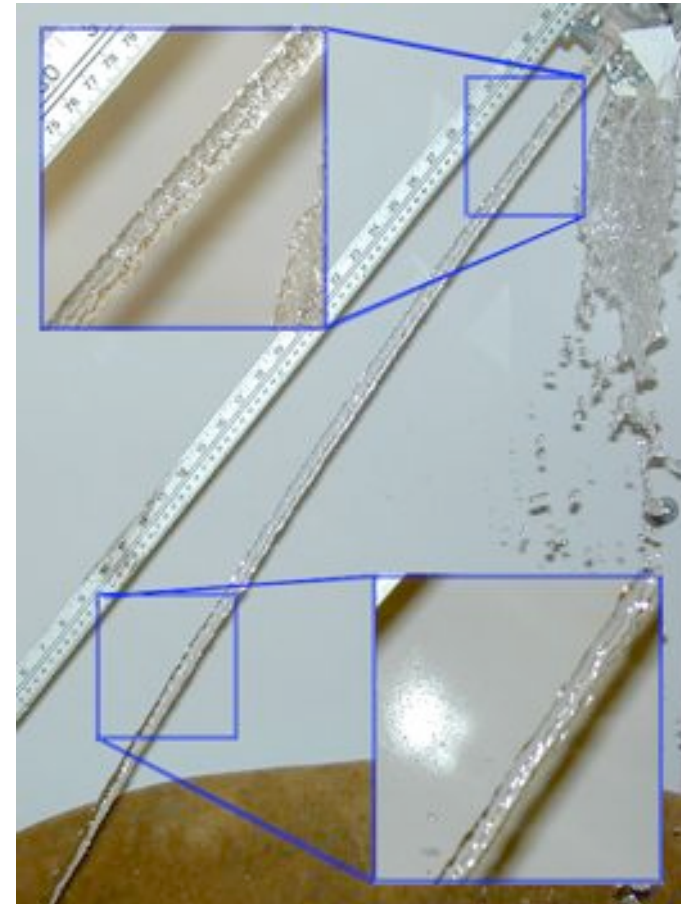
vortex flow



Experiments show cylindrical jets can be sufficiently smooth for beam-line protection

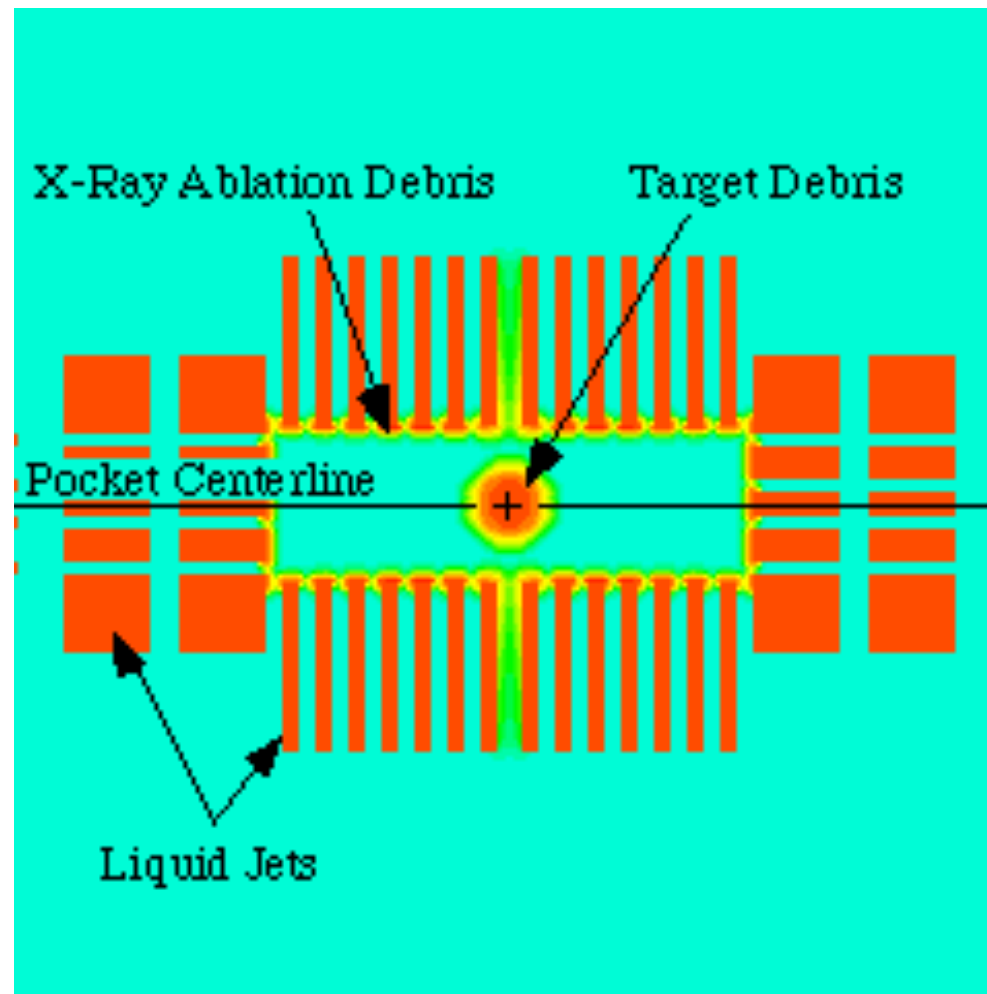


First UCB cylindrical jet experiment
7/13/2000



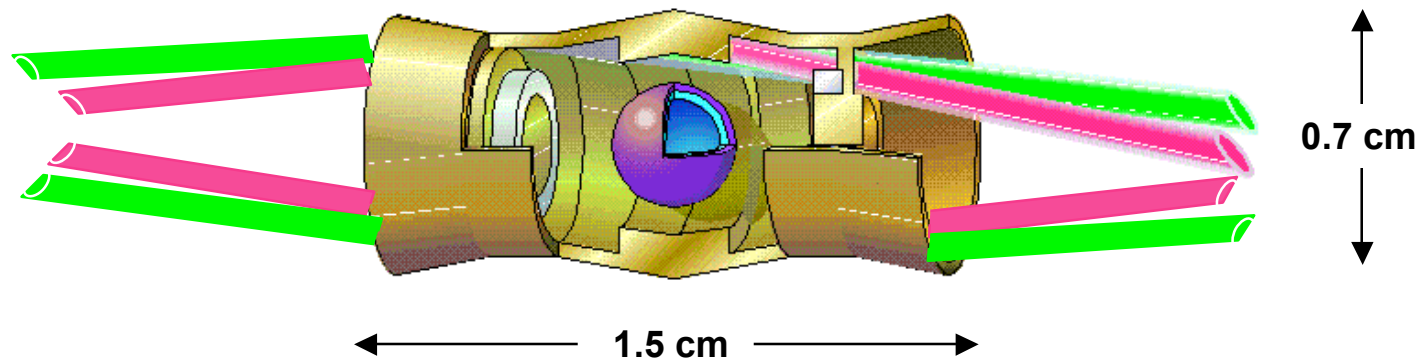
$d_j = 1.3 \text{ cm}$ $Re = 70,000$
 $v_j = 4.9 \text{ m/s}$

Chamber dynamics are simulated using the Tsunami code



Heavy Ion Fusion has traditionally assumed that targets will use “Indirect Drive” (NIF baseline)

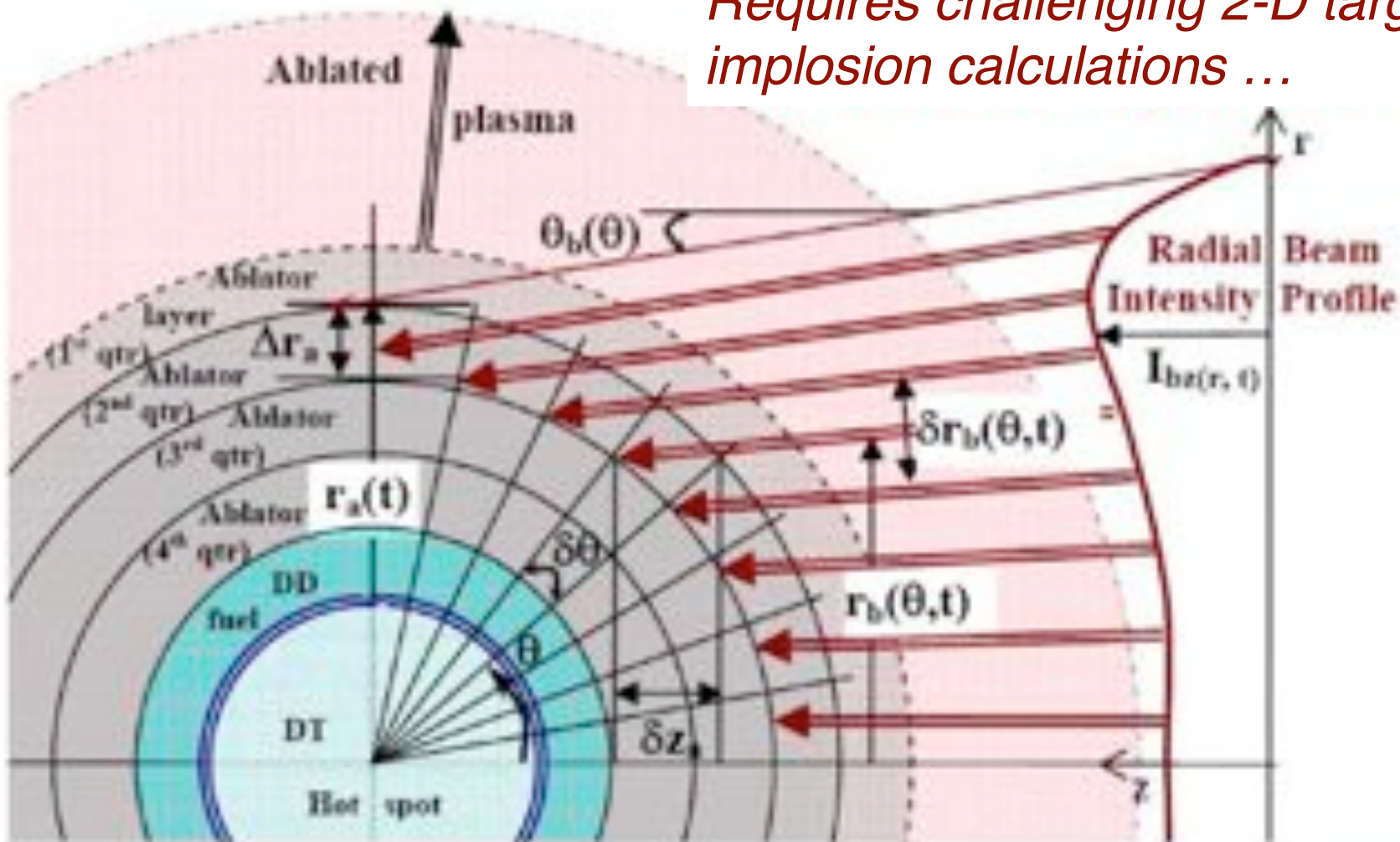
Ion Beams \Rightarrow *x-rays*
X-rays symmetrize in *hohlraum*



Requires *~ 500 Terawatts (!!)* (3 - 7 MJ in ~ 10 ns)
Ion Range \Rightarrow *1- 10 GeV* (about 1/3 the speed of light)

New target ideas include ion direct drive, and even “polar direct drive”

Requires challenging 2-D target implosion calculations ...



Direct drive isn't entirely a new idea (for electrons, ions, or teapots)



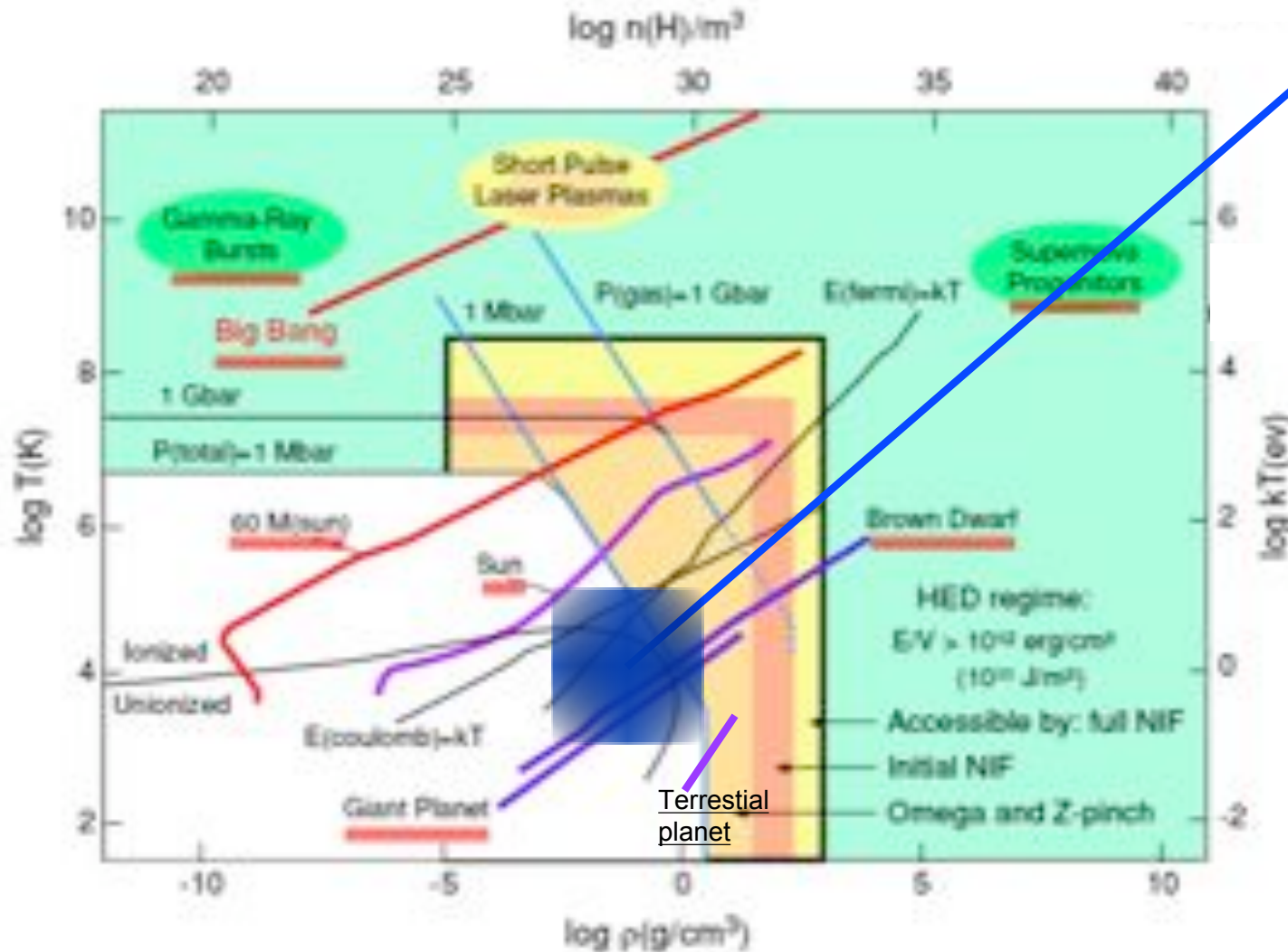
(R. L. McCrory, invited review, Meeting of the APS Division of Plasma Physics, 1981)



**"Guess we need a bigger kitchen
and better flame throwers!"**



HIFS-VNL's near-term mission: exploring the novel properties of matter in the “Warm Dense Matter” (WDM) regime



The regime in ρ - T space that is accessible by **beam driven experiments** lies square in the interiors of gas planets and low mass stars

Figure adapted from “Frontiers in HEDP: the X-Games of Contemporary Science:”

Talk Outline

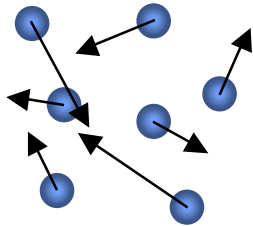
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Plasmas and beams consist of a large number of **interacting charged particles**; a variety of models are used

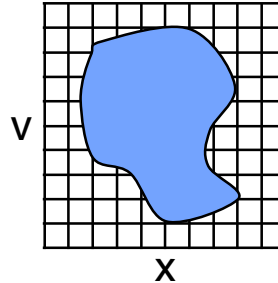
- **Particle motion** mathematically described by
 - Lagrangian approach: evolution of discrete markers
 - Eulerian approach: evolution of an incompressible fluid in phase-space:
 - with collisions: Boltzmann/Fokker-Planck eq.
 - no collisions: Vlasov eq.
 - in real space: fluid/MHD eq.
- **Interactions** mathematically described by
 - Lagrangian approach: sum over all markers
 - instantaneous: Green functions
 - with retardation: retarded Green functions
 - Eulerian approach: fields
 - instantaneous: Poisson, “Darwin” (magneto-inductive)
 - with retardation and EM waves: Maxwell

Modeling involves choices

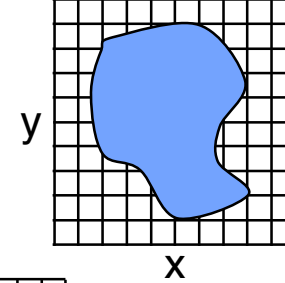
- In summary, the modeling of a plasma implies the modeling of:
a collection of particles fluid cells in phase-space fluid cells in configuration space



or

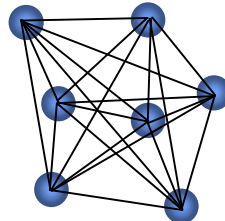


or

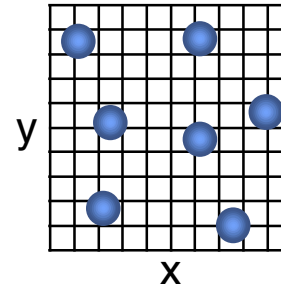


interacting either:

directly



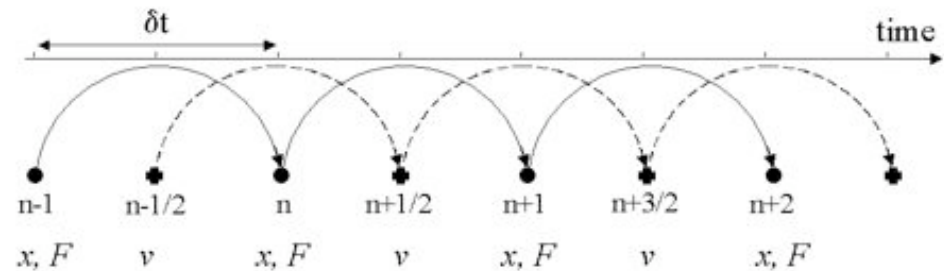
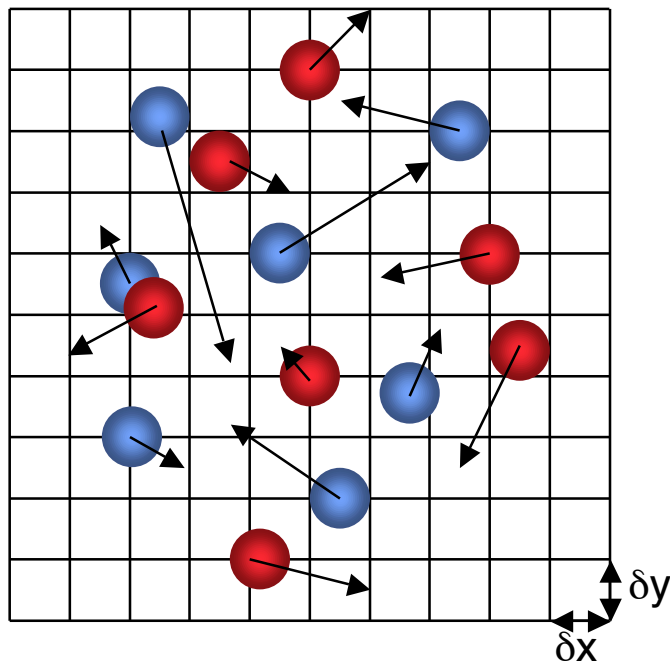
or through a field



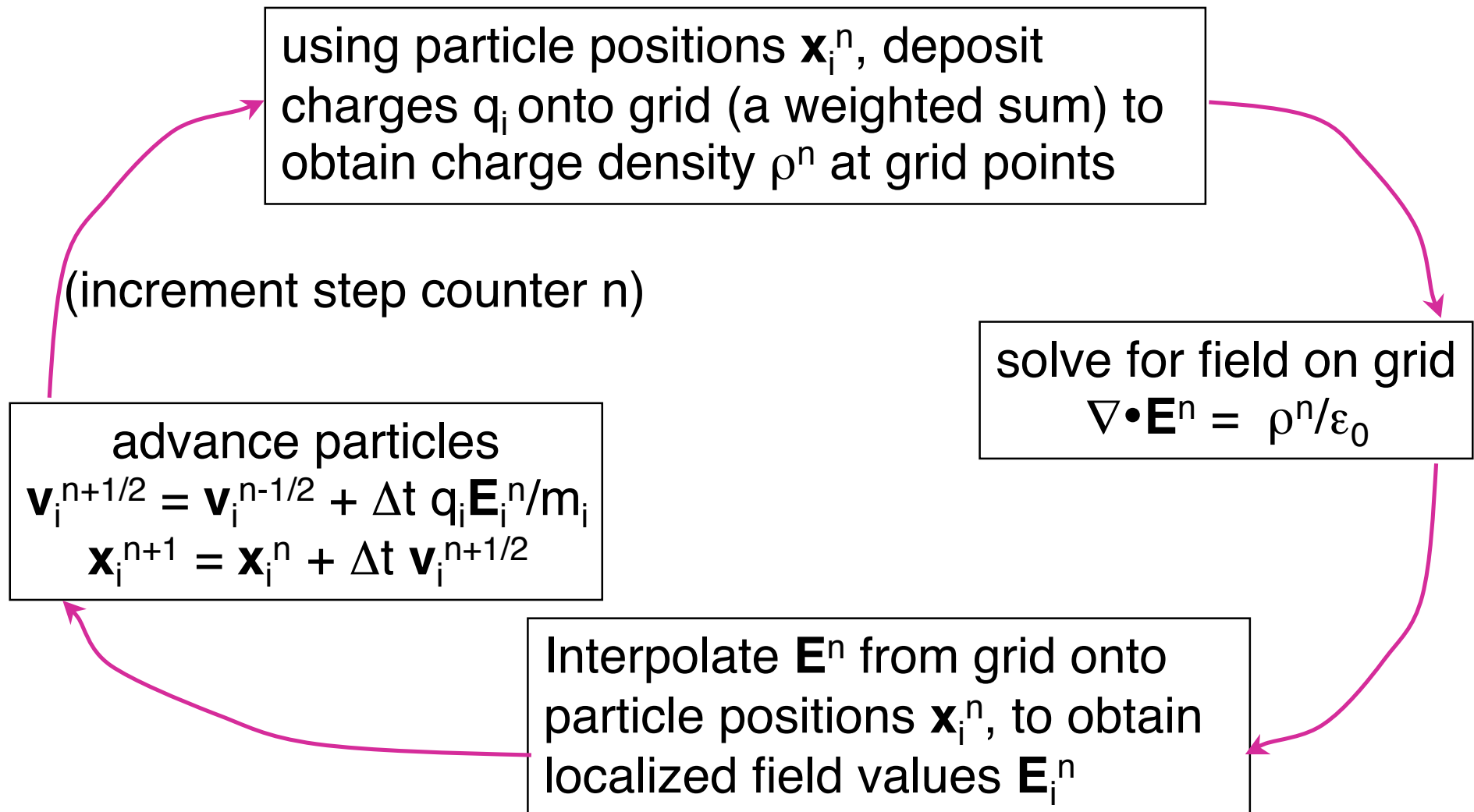
- The numerical integration leads to more choices
 - Partial differential equations: finite-differences/volumes/elements, Monte-Carlo, semi-Lagrangian, ...
 - Time integration: explicit/implicit, “symplectic,” ...
 - Direct interaction: direct summation, multipole expansion (tree-codes), ...
 - ...

We use (primarily) the Particle-In-Cell (PIC) method

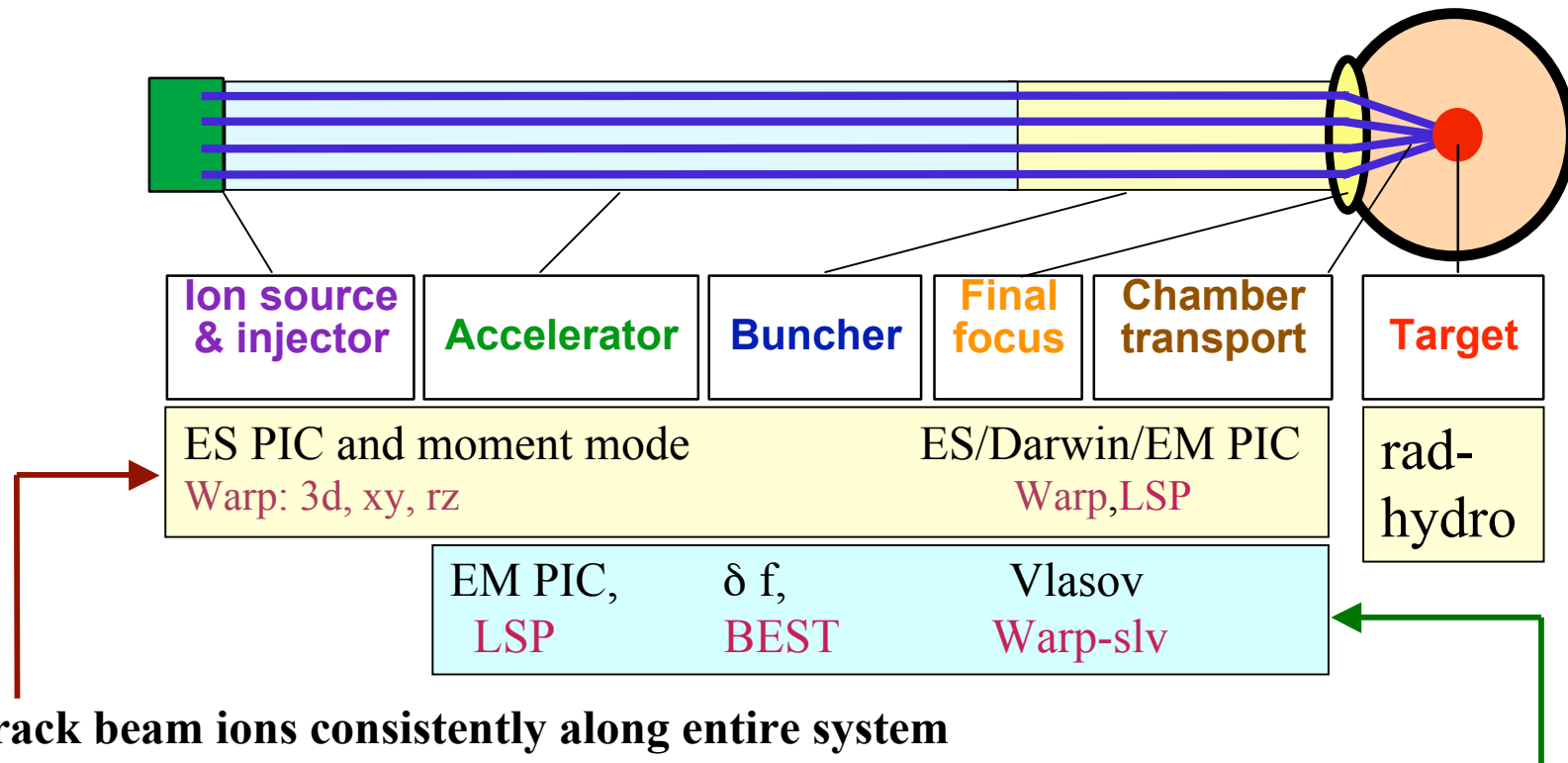
- We use macroparticles (1 macroparticle = many real particles)
- We compute the force (fields) on a grid (electrostatic or EM)
- We advance particle and fields by finite time steps



Simulation loop connects particle advance & field solution (here, a simple electrostatic example)



HIF systems are broken into pieces that can be studied separately



Track beam ions consistently along entire system

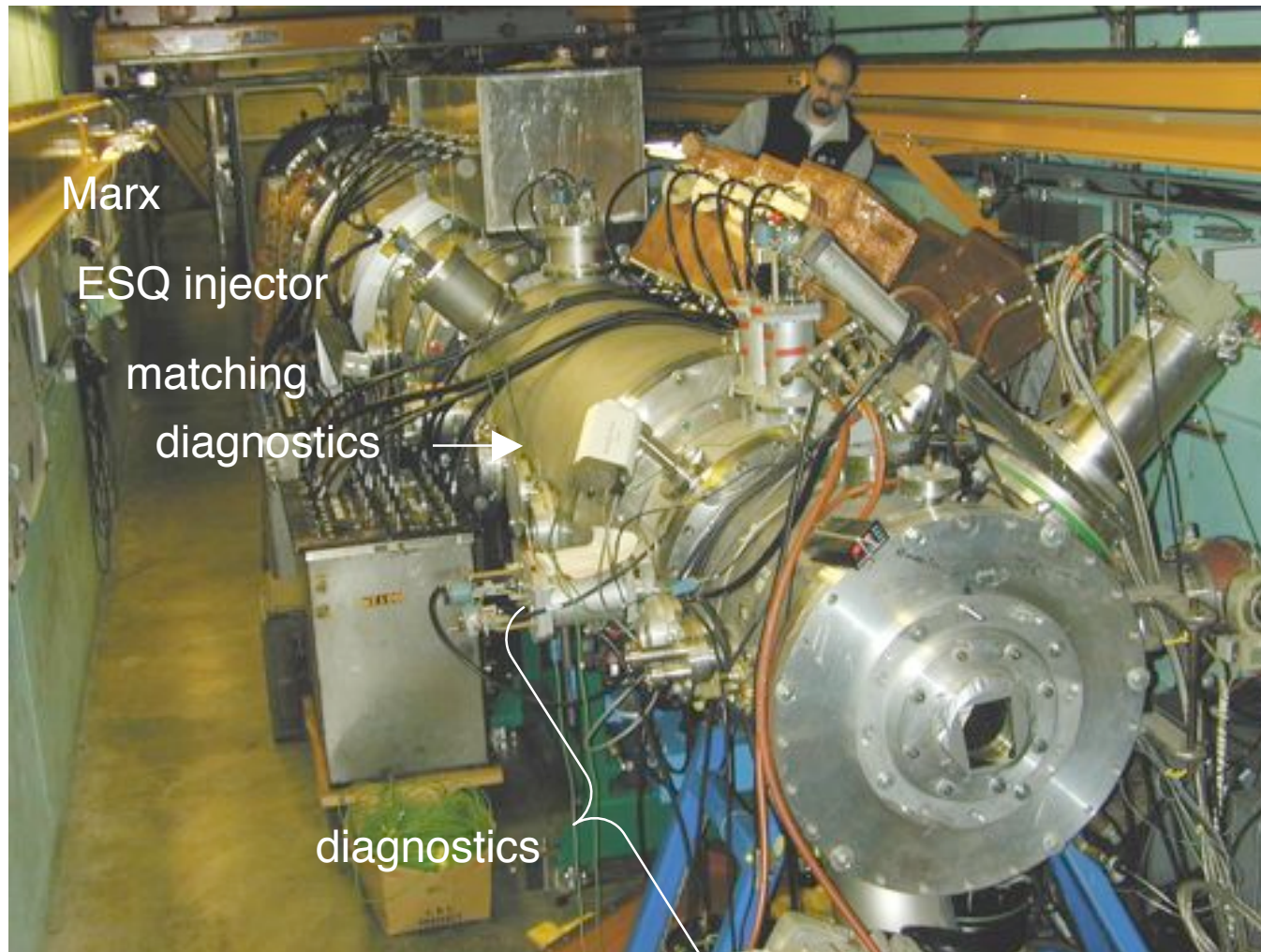
Study instabilities, halo, electrons, ..., via coupled detailed models

- We compute on Mac's, pc's, linux boxes and clusters, parallel supercomputers
- Even on supercomputers, simulation of all the real particles is generally impractical
=> we have to make approximations!

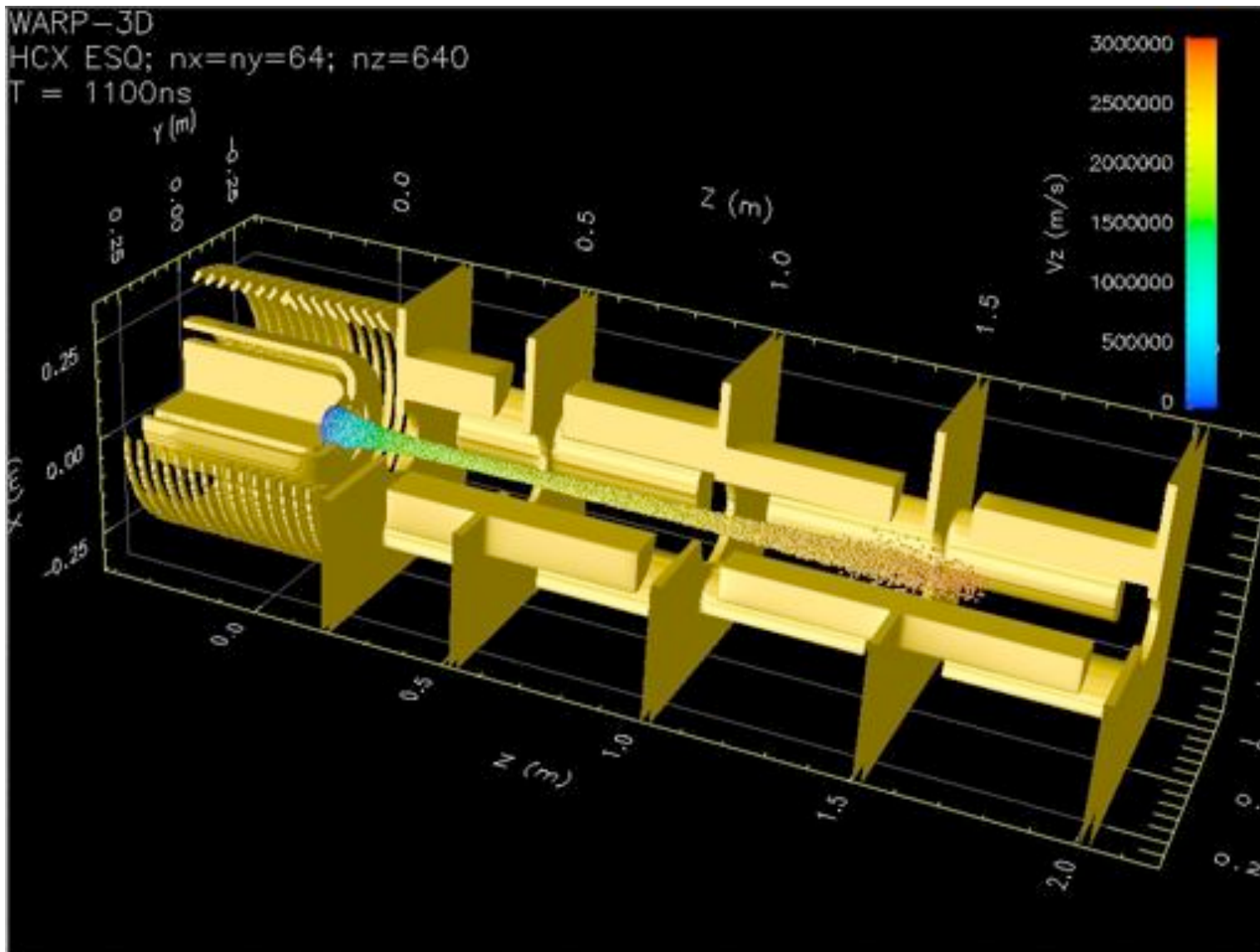
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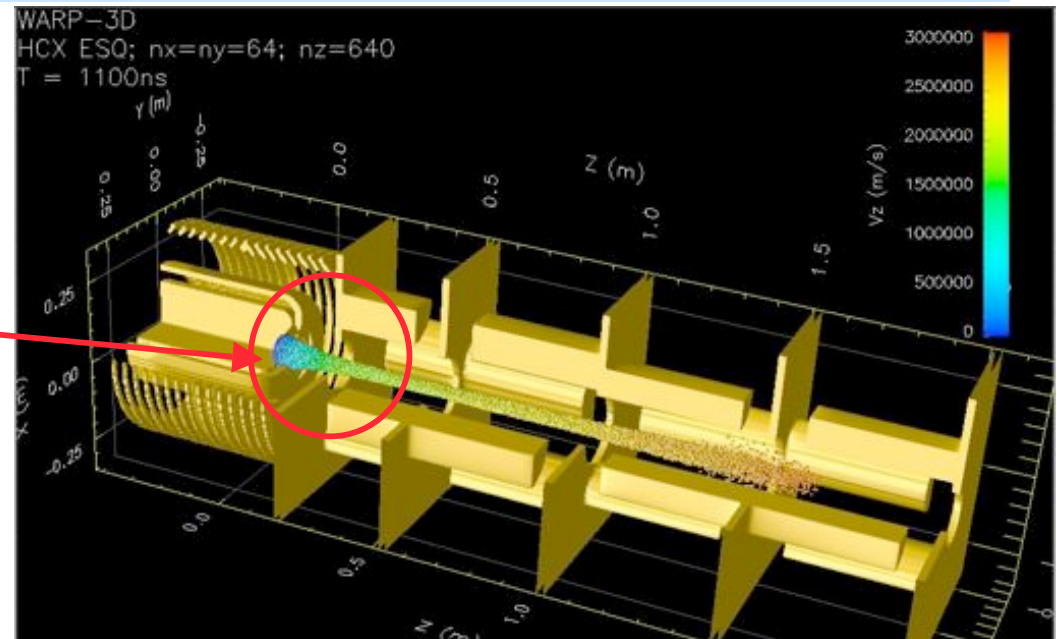
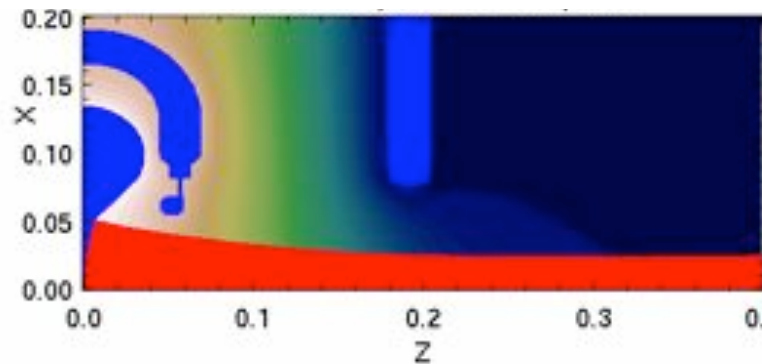
High Current Experiment (HCX) at LBNL offers 1-2 MV ion beams



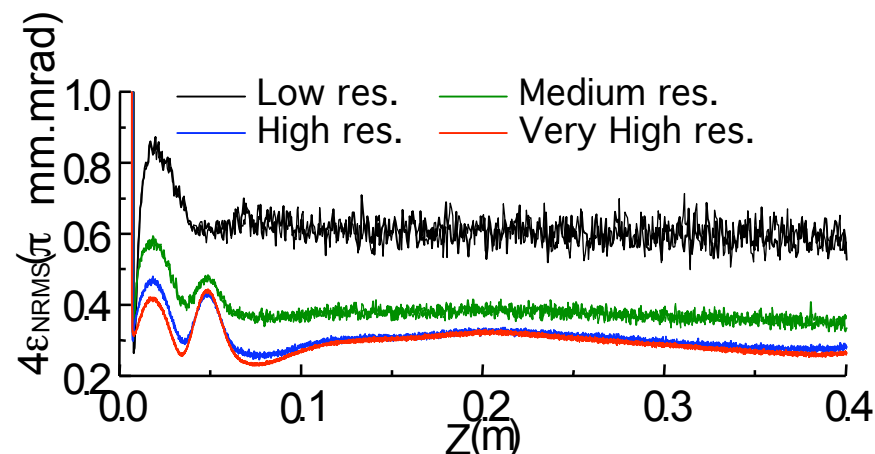
3-D WARP simulation of HCX injector



Modeling of source is critical; collisionless beams have a “long memory”



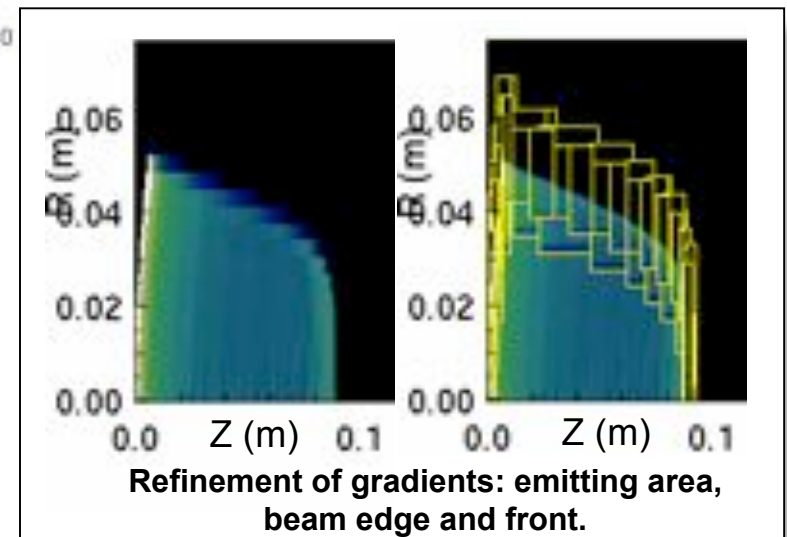
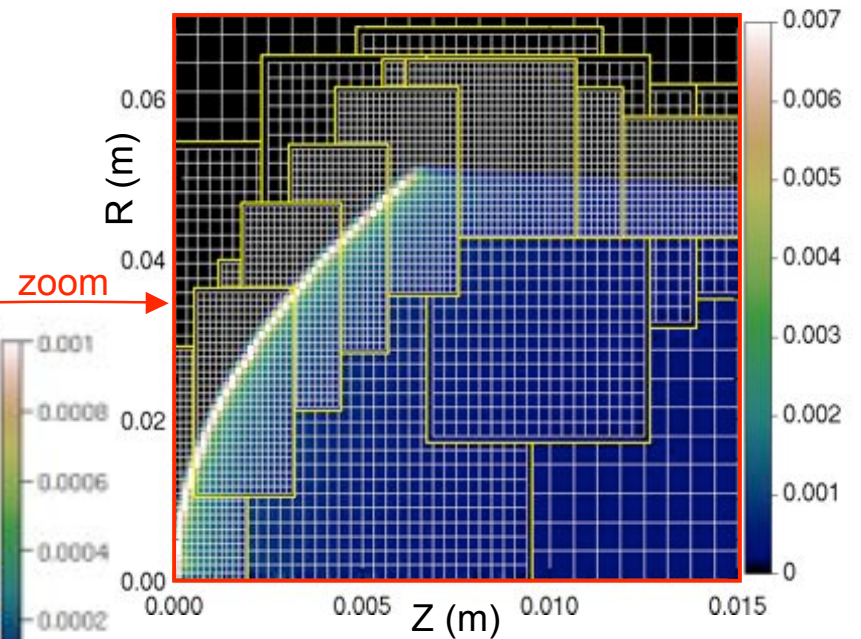
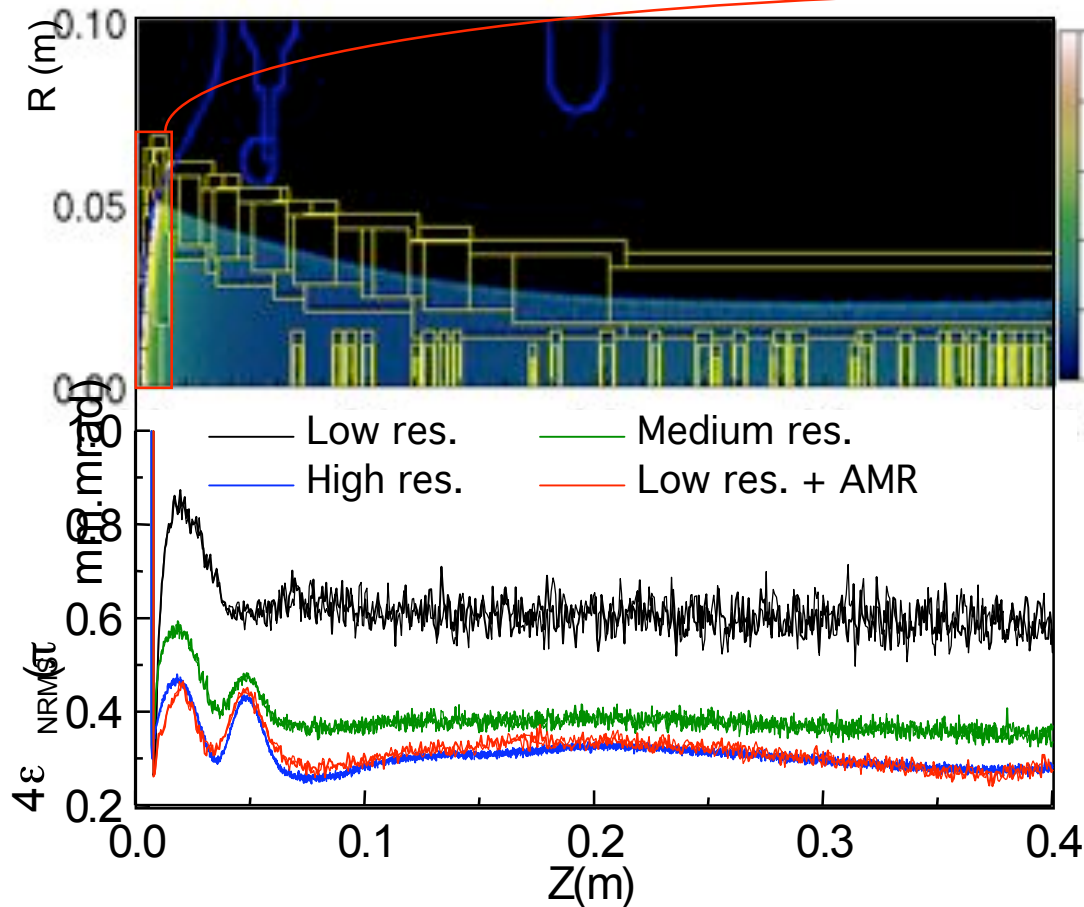
WARP-RZ (axi-symmetric) simulations of source show that a fairly high resolution is needed to reach convergence



Run	Grid size	Nb particles
Low res.	56x640	~1M
Medium res.	112x1280	~4M
High res.	224x2560	~16M
Very High res.	448x5120	~64M

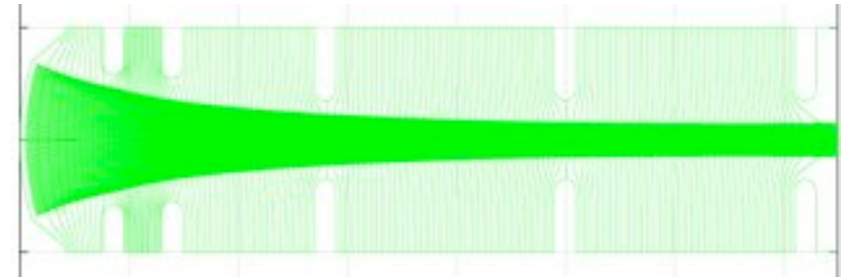
We have merged PIC+AMR: speedup ~ 10.5

Run	Grid size	Nb particles
Low res.	56x640	$\sim 1\text{M}$
Medium res.	112x1280	$\sim 4\text{M}$
High res.	224x2560	$\sim 16\text{M}$
Low res. + AMR	56x640	$\sim 1\text{M}$



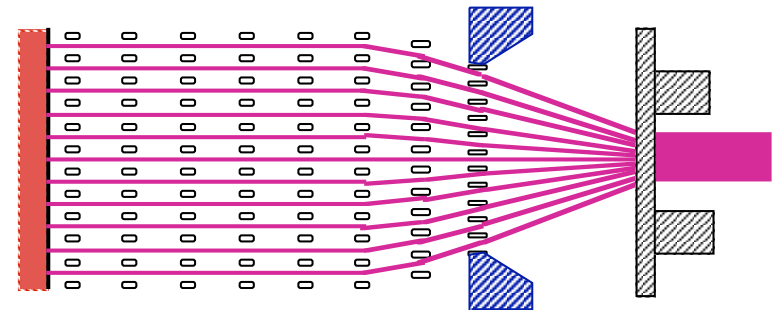
We have explored a compact ion source approach

- **Traditional**: use a large diameter but low current density single-aperture ion source.



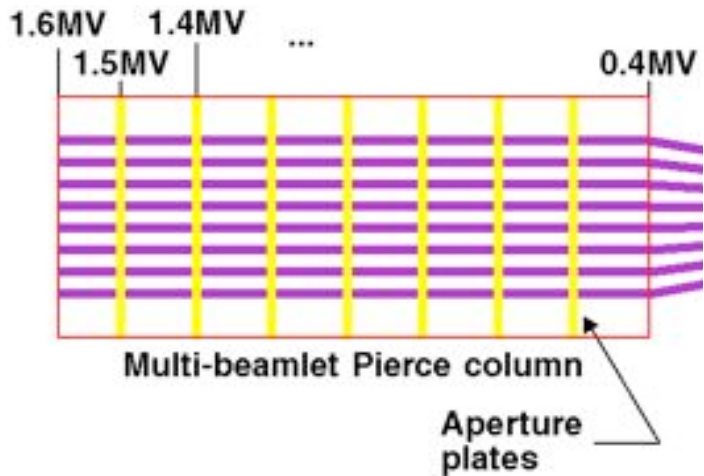
4 mA/cm²

- **New**: extract hundreds of mm-scale high current density *beamlets*, from a multiple-aperture ion source.

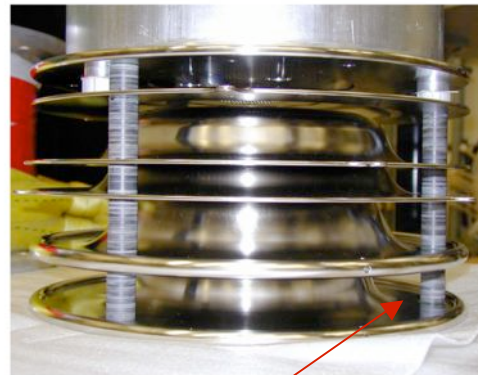


100 mA/cm²/beamlet

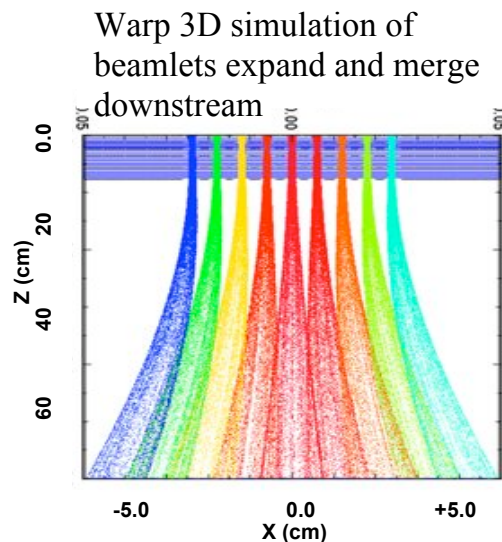
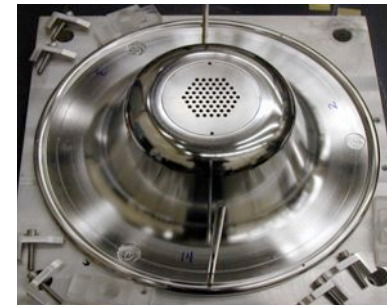
Merging beamlet high gradient experiment: simulation challenging: large 3-D run on parallel supercomputer.



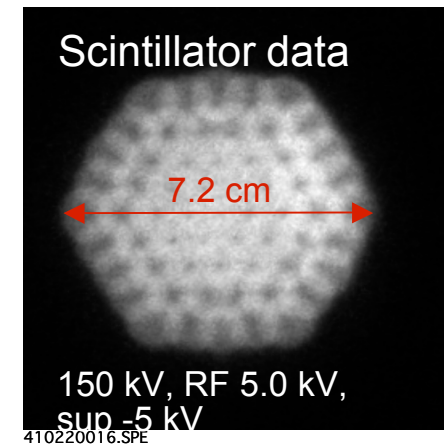
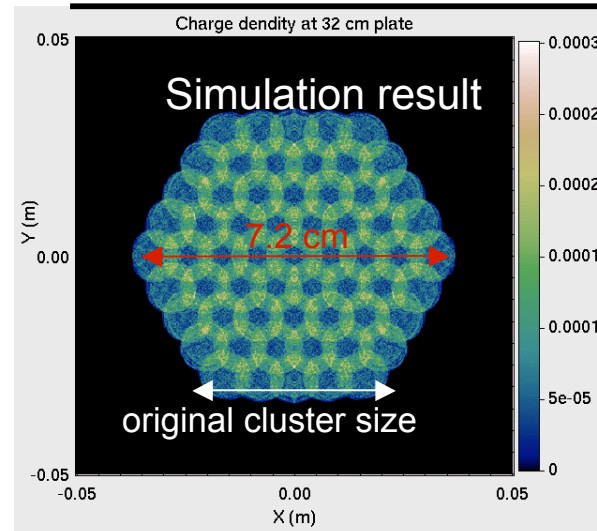
18.3cm



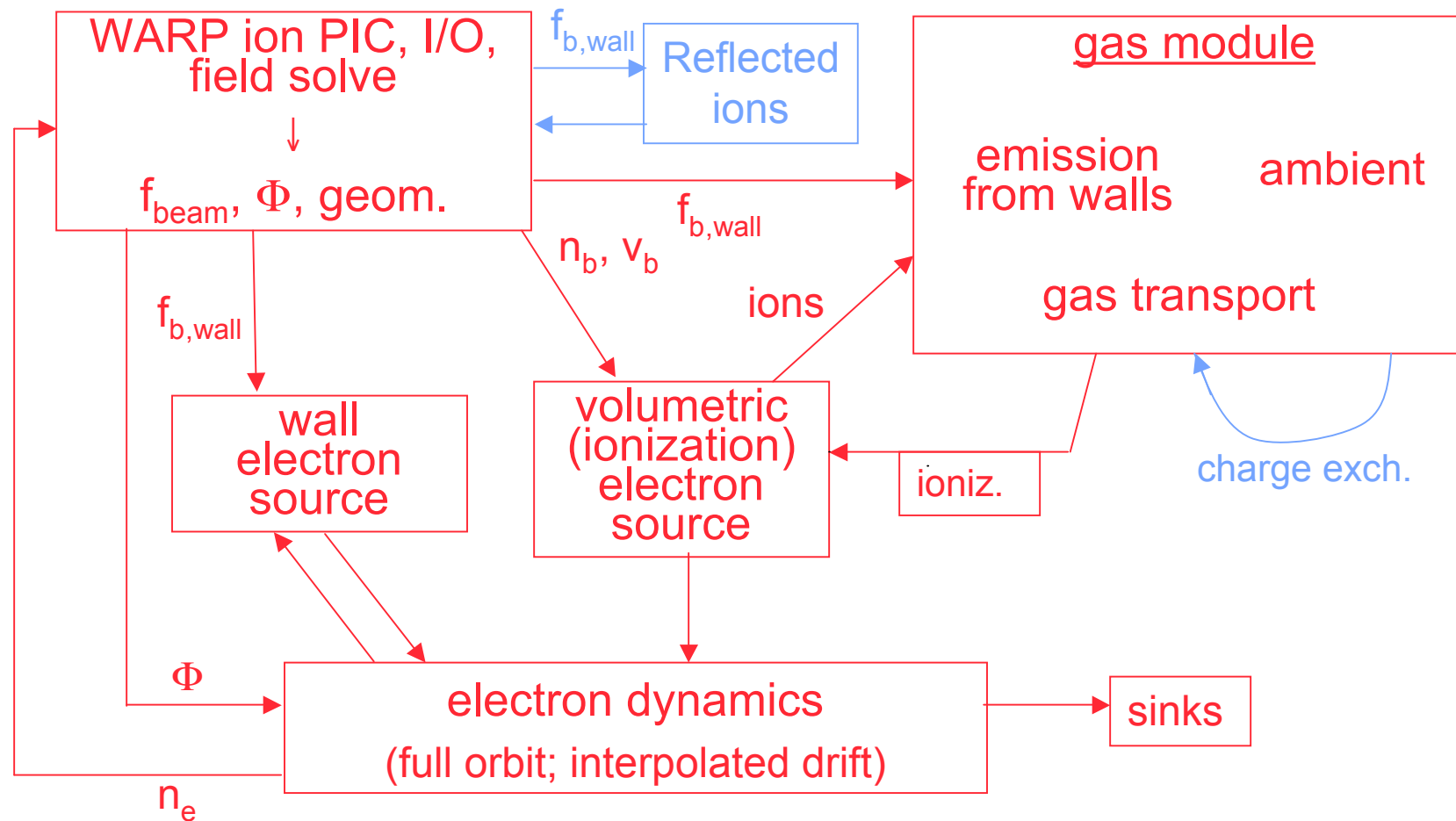
High Gradient Insulators held 30 kV/cm



Z = 15 cm

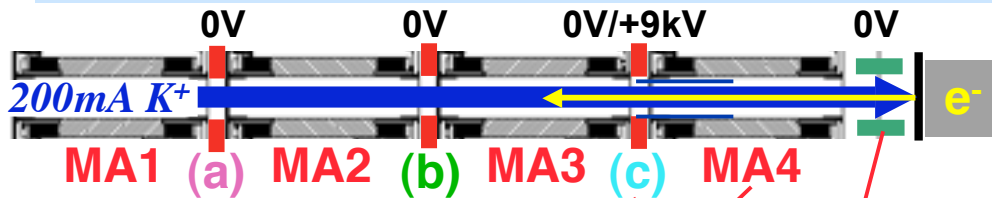


“Roadmap” for self-consistent modeling of beam with electron cloud & gas effects

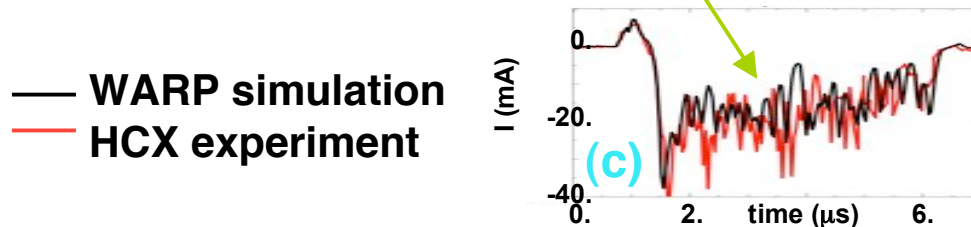
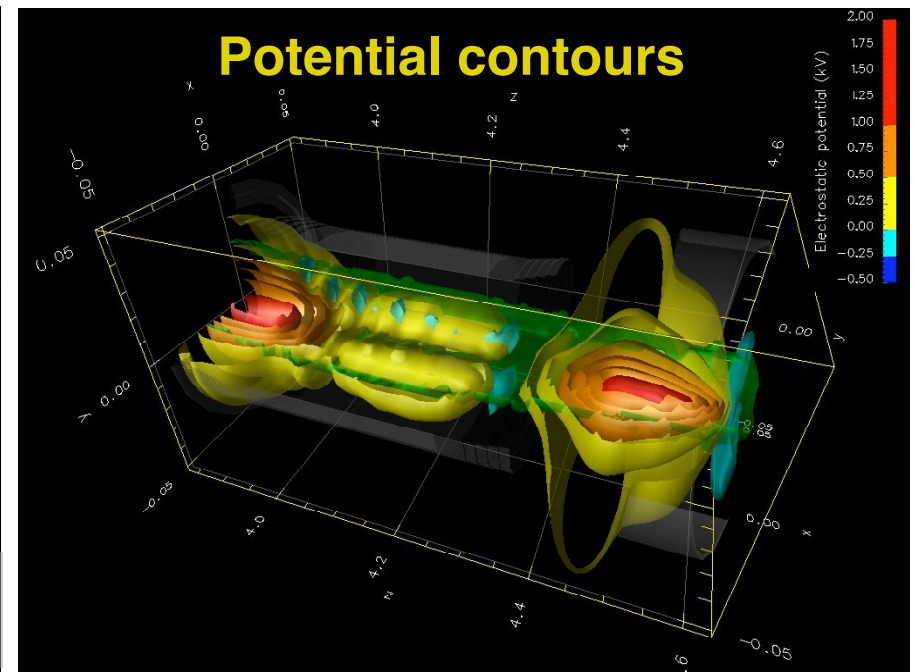
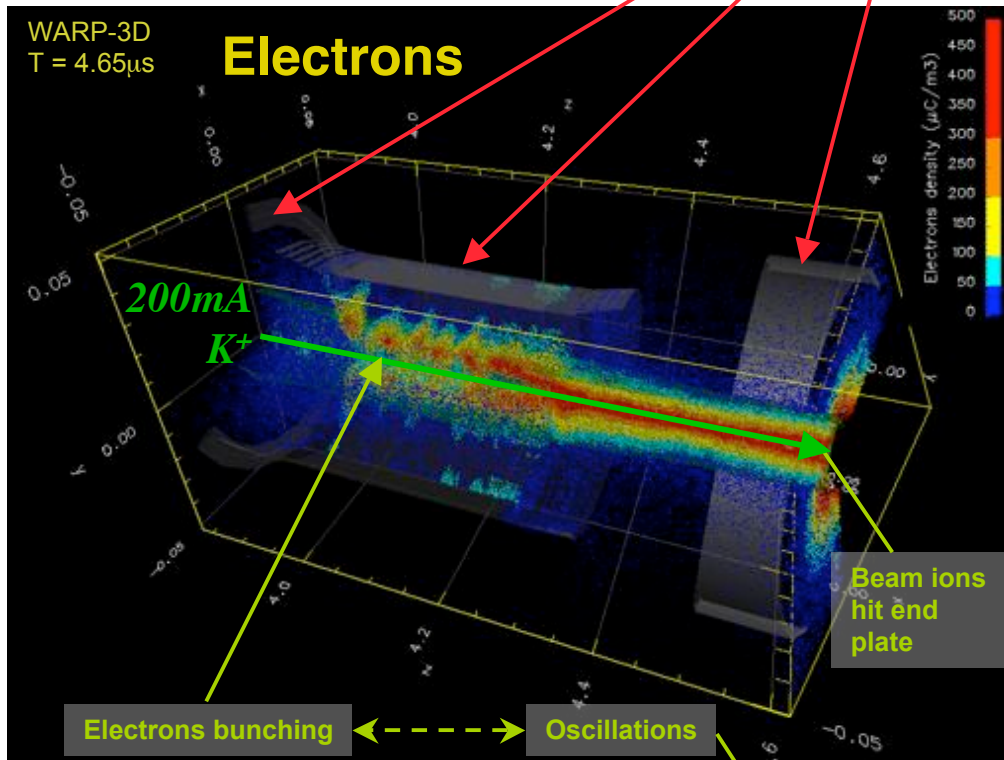


- Key: **operational**; **partially implemented** (5/6/05)

Beam hits end-plate in HCX to generate copious electrons; bunching observed in simulations and experiments

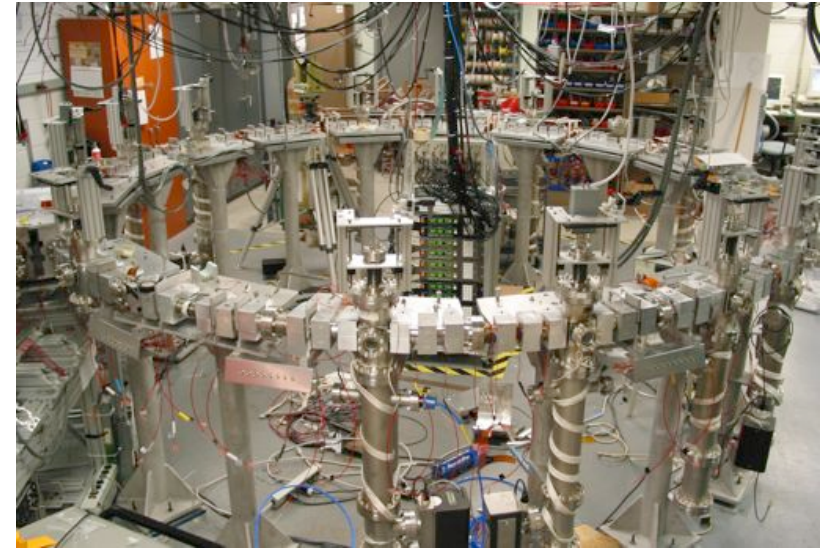
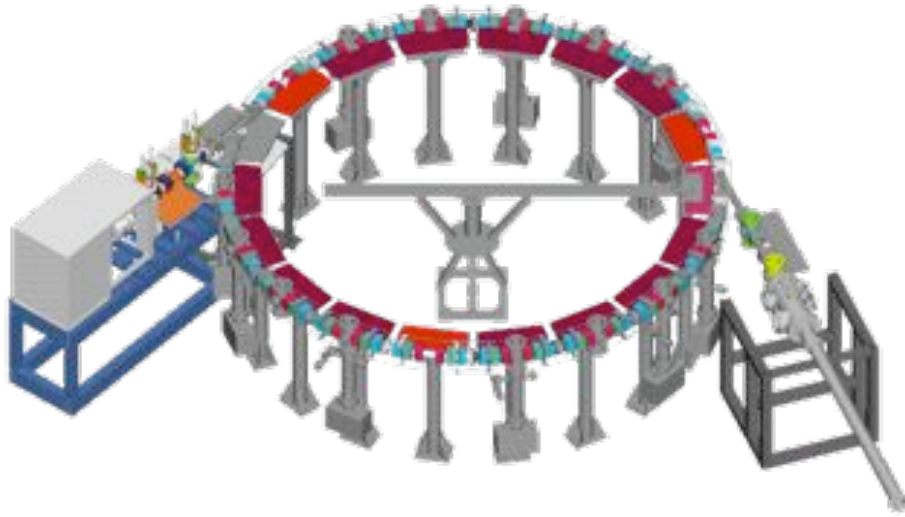


Wavelength of ~5 cm, growing from near center of 4th quad. magnet

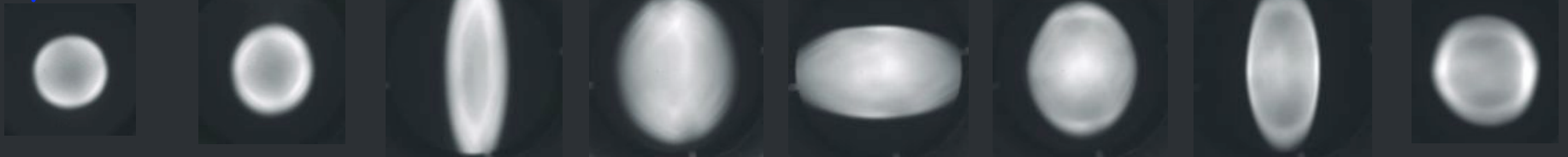


~6 MHz signal in clearing electrode (C)

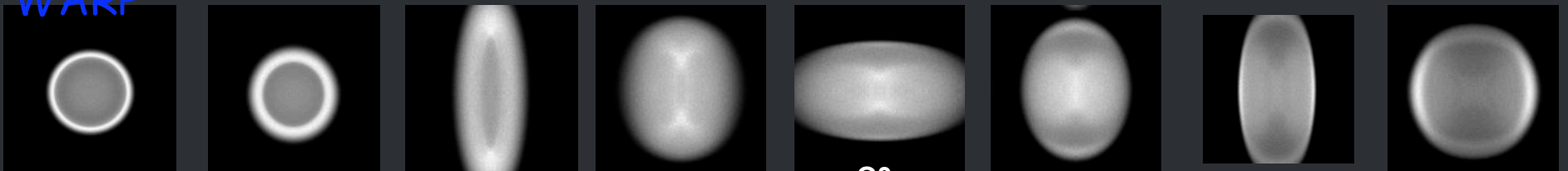
WARP simulations support the University of Maryland Electron Ring experiments



Experiment



WARP



Q1

Q3

Q4

The rings are due to edge lensing

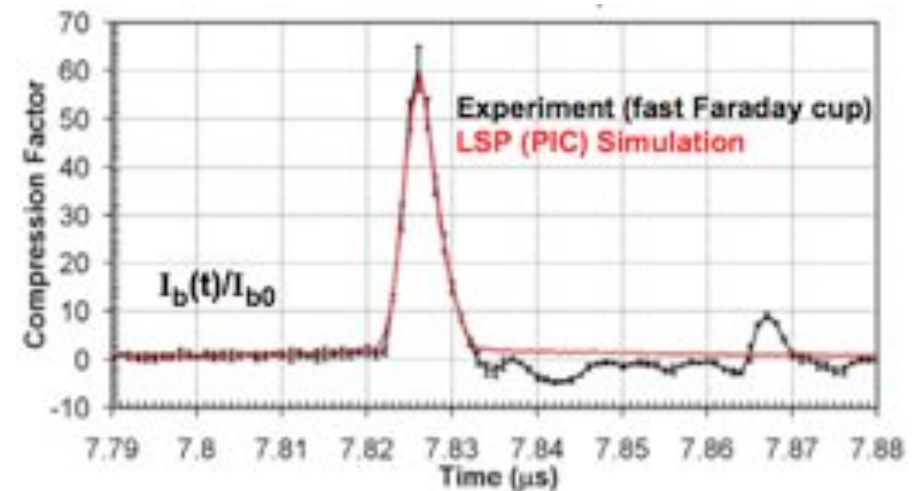
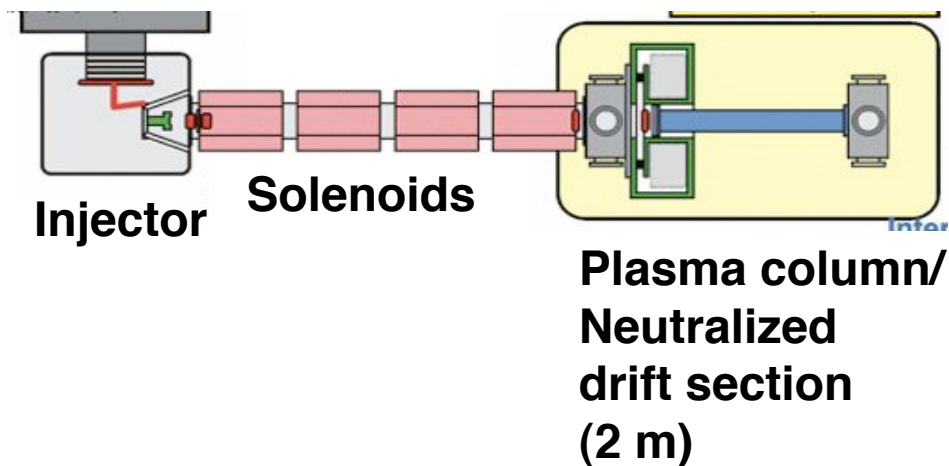
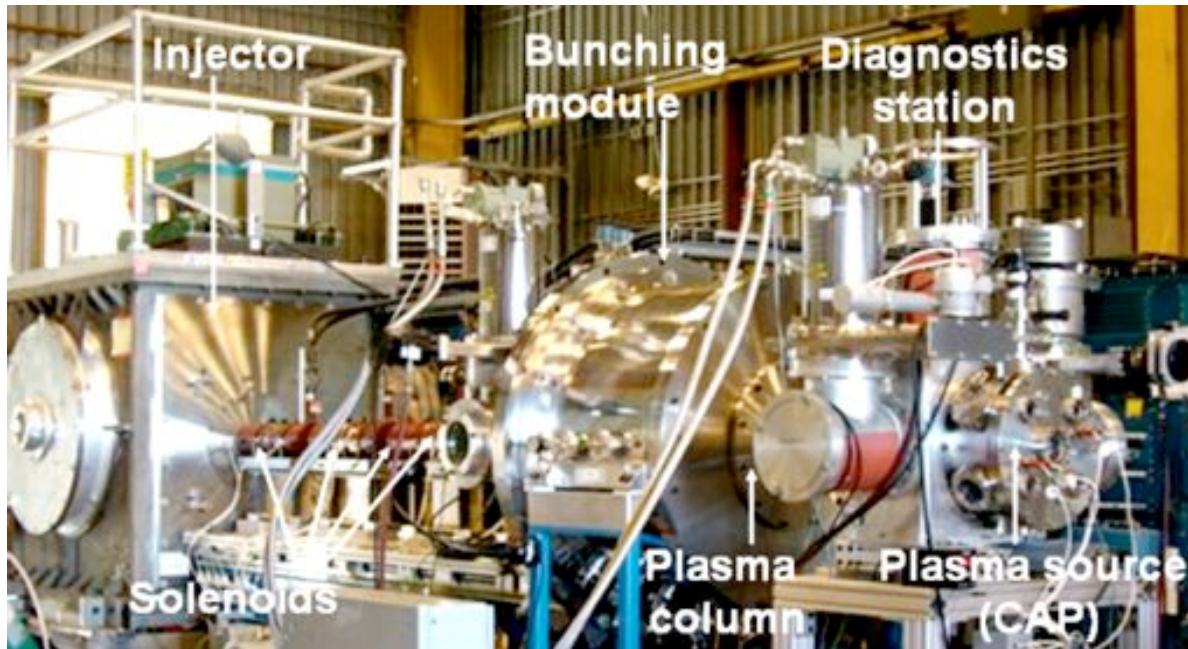
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Neutralized drift compression and focusing open up new possibilities

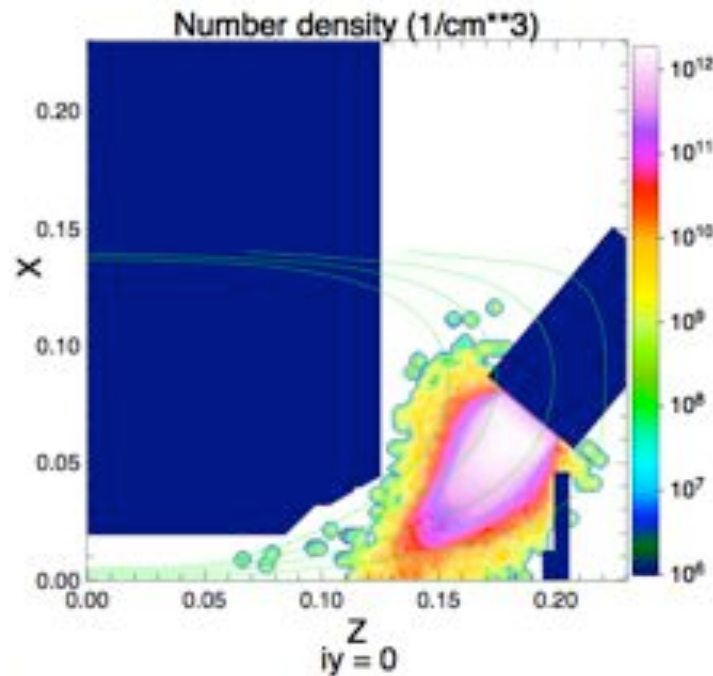
- Eliminating beam's space charge repulsion allows:
 - much shorter pulses
 - a much tighter transverse focus
- Enables near-term Warm Dense Matter studies
- May enable ion direct drive (short range needed \rightarrow low K.E. ions \rightarrow high I)
- Issues:
 - Background plasma density must be $>$ (or at least $=$) beam density
 - How to get plasma where it is needed, especially in final focusing solenoid
 - How to prevent plasma from flowing upstream

In NDCX-1, a velocity “tilt” accelerates the beam tail and decelerates the head, yielding ~ 70x pulse compression

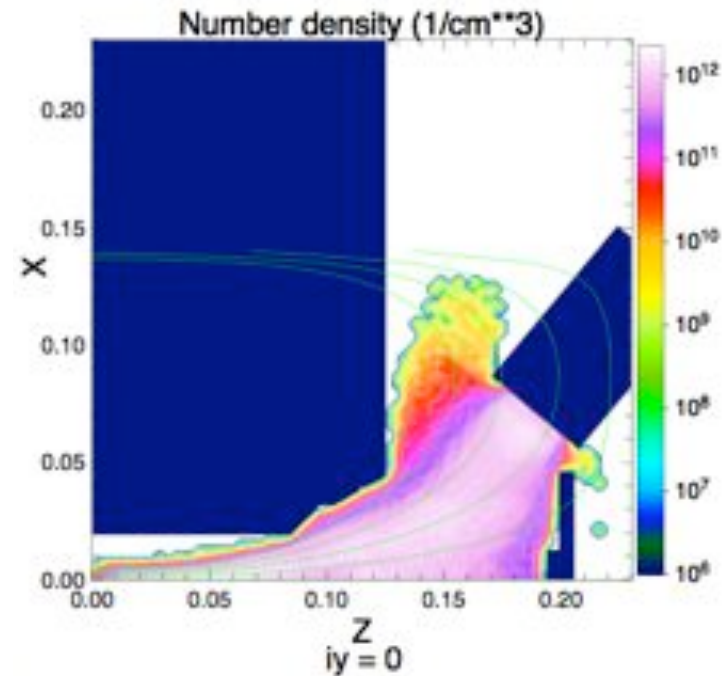


We simulate injection from Cathodic-Arc Plasma sources

1.2 ns



4.5 ns



Here, the Warp code was used; LSP has been used extensively

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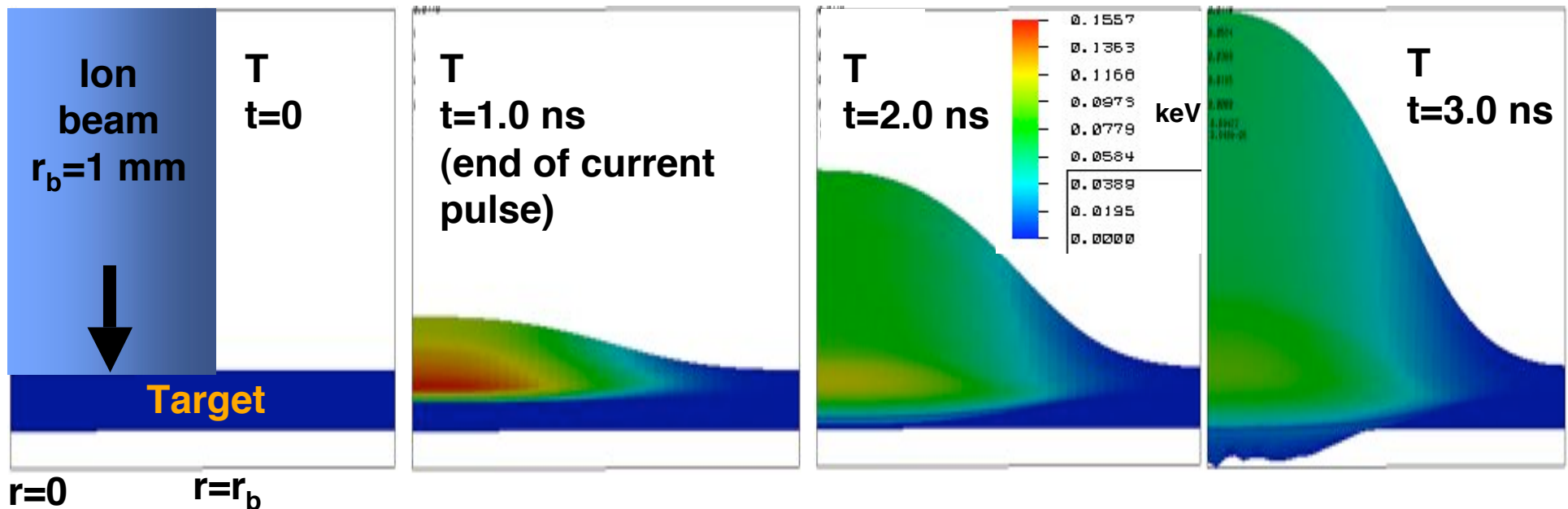
We use the 3D LLNL code HYDRA for target studies

- state-of-the-art multi-physics radiation transport/hydrodynamics code¹
- Initial explorations of ion beam interactions with foil targets²

Illustrative example of non-uniform heating:

2D R-Z, time-dependent simulations of 20 MeV Ne beam hitting 10% Al foam foil

Temperature contour plots



1. M. M. Marinak, G. D. Kerbel, N. A. Gentile, O. Jones, D. Munro, S. Pollaine, T. R. Dittrich, and S. W. Haan, Phys. Plasmas 8, 2275 (2001).

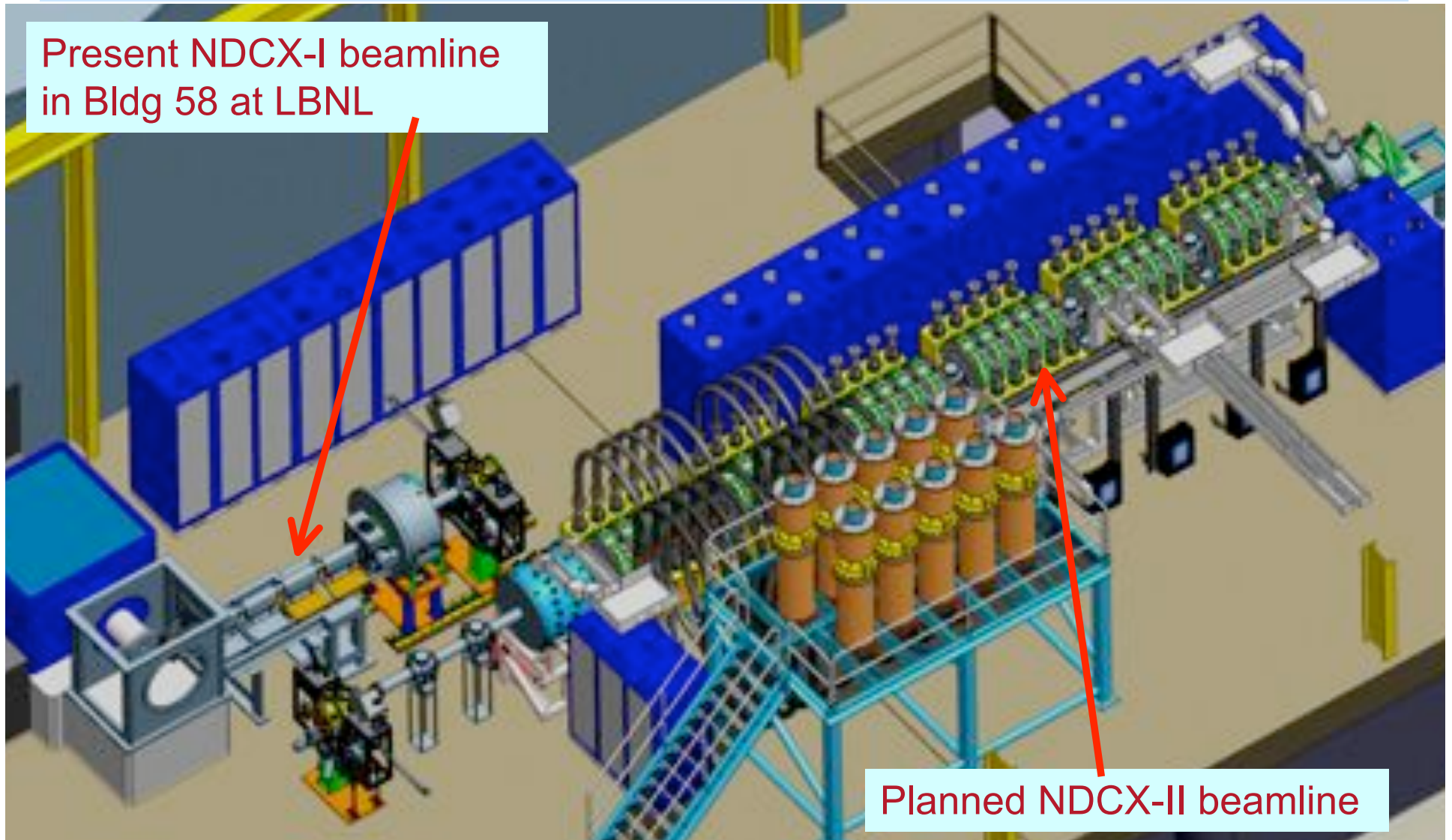
2. Simulation collaborators: J.J. Barnard, G.E. Penn, J. S. Wurtele, P. Santhanam, A. Friedman, M. M. Marinak

Talk Outline

- Fusion
 - Introduction
 - The Heavy Ion Fusion program
- Modeling plasmas and beams - taxonomy of methods
- HIF experiments and simulations
 - Non-neutral beams in accelerators
 - Neutralized beams in plasmas
 - Targets
- The next step - NDCX-II

Uniform “Bragg peak” heating of foils, and ion direct drive studies, require a more capable facility than NDCX-I

Present NDCX-I beamline
in Bldg 58 at LBNL



For Warm Dense Matter studies,
the NDCX-II beam must be
accelerated to 3-4 MeV and
compressed to ~ 1 ns (~ 1 cm)

LITHIUM ION BEAM BUNCH

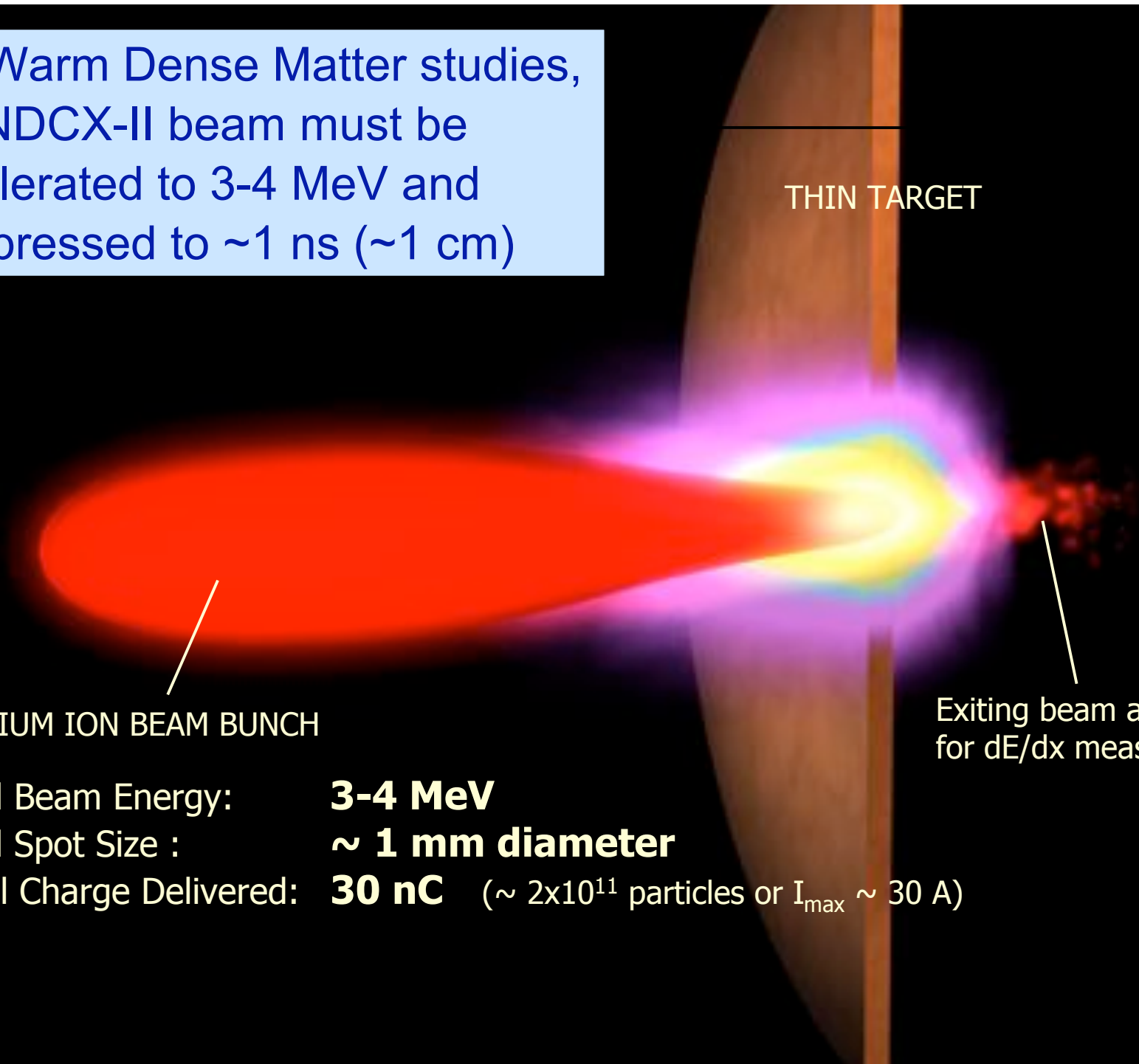
Final Beam Energy: **3-4 MeV**

Final Spot Size : **~ 1 mm diameter**

Total Charge Delivered: **30 nC** ($\sim 2 \times 10^{11}$ particles or $I_{\text{max}} \sim 30$ A)

THIN TARGET

Exiting beam available
for dE/dx measurement



Induction cells for NDCX-II are available from LLNL's decommissioned ATA facility



Test stand
has begun
to verify
performance

solenoid

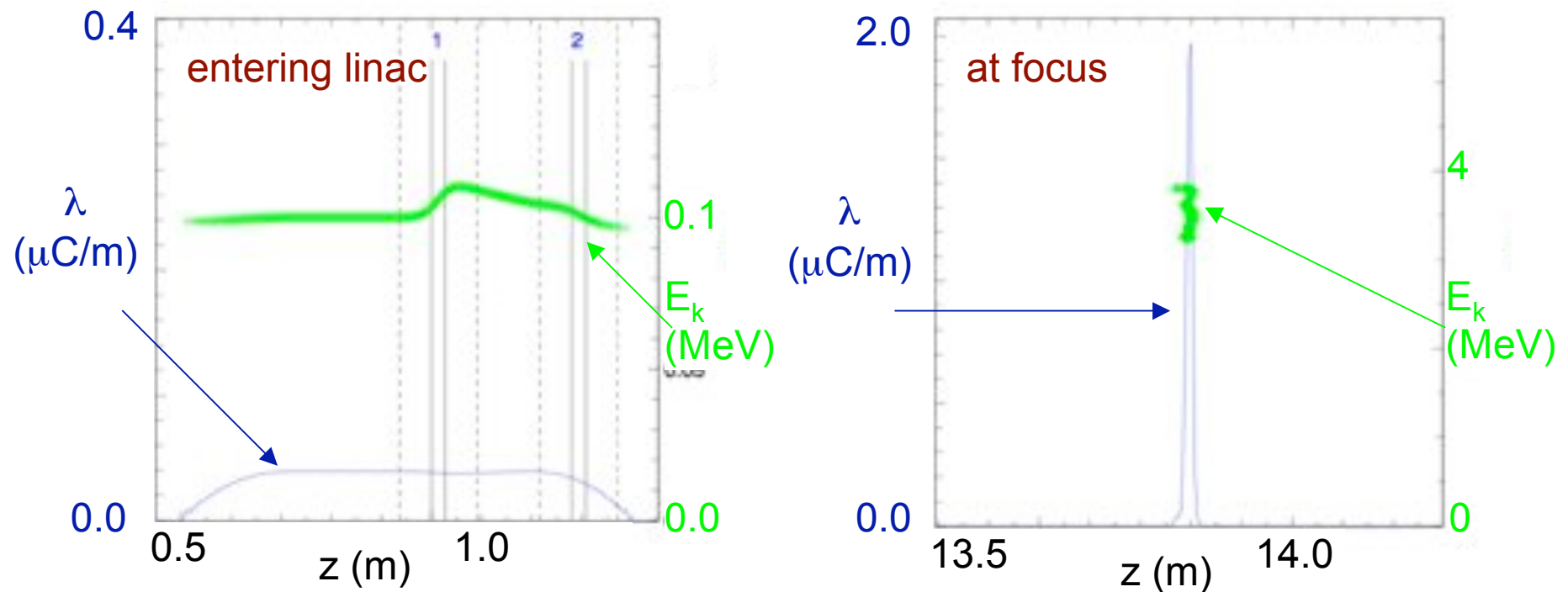
water cooling



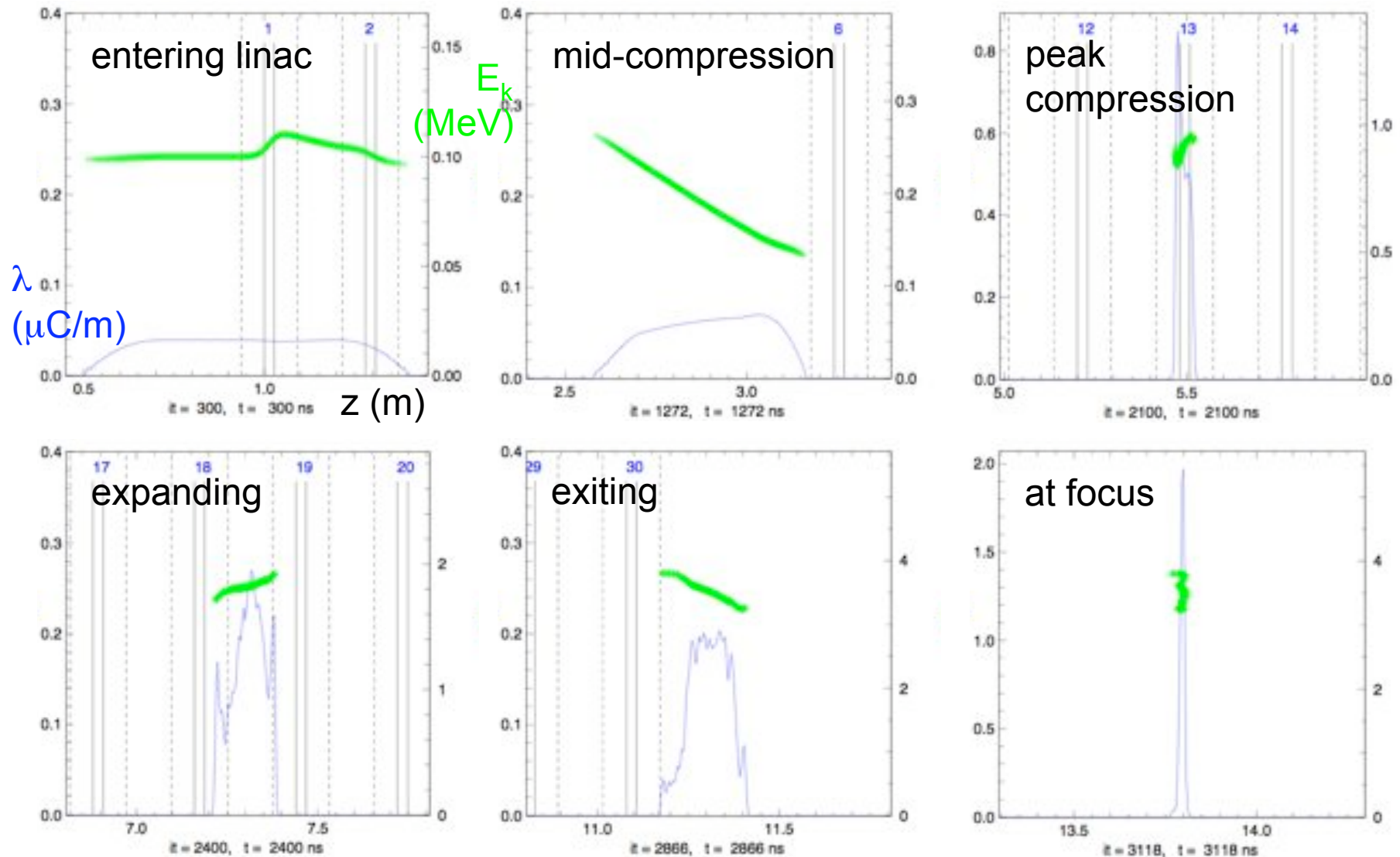
We are well on our way toward a physics design for NDCX-II

- Accel-decel injector produces a ~ 100 keV Li^+ beam with ~ 67 mA flat-top
- Induction accelerates it to 3.5 MeV at 2 A
- The 500 ns beam is compressed to ~ 1 ns in just ~ 14 m

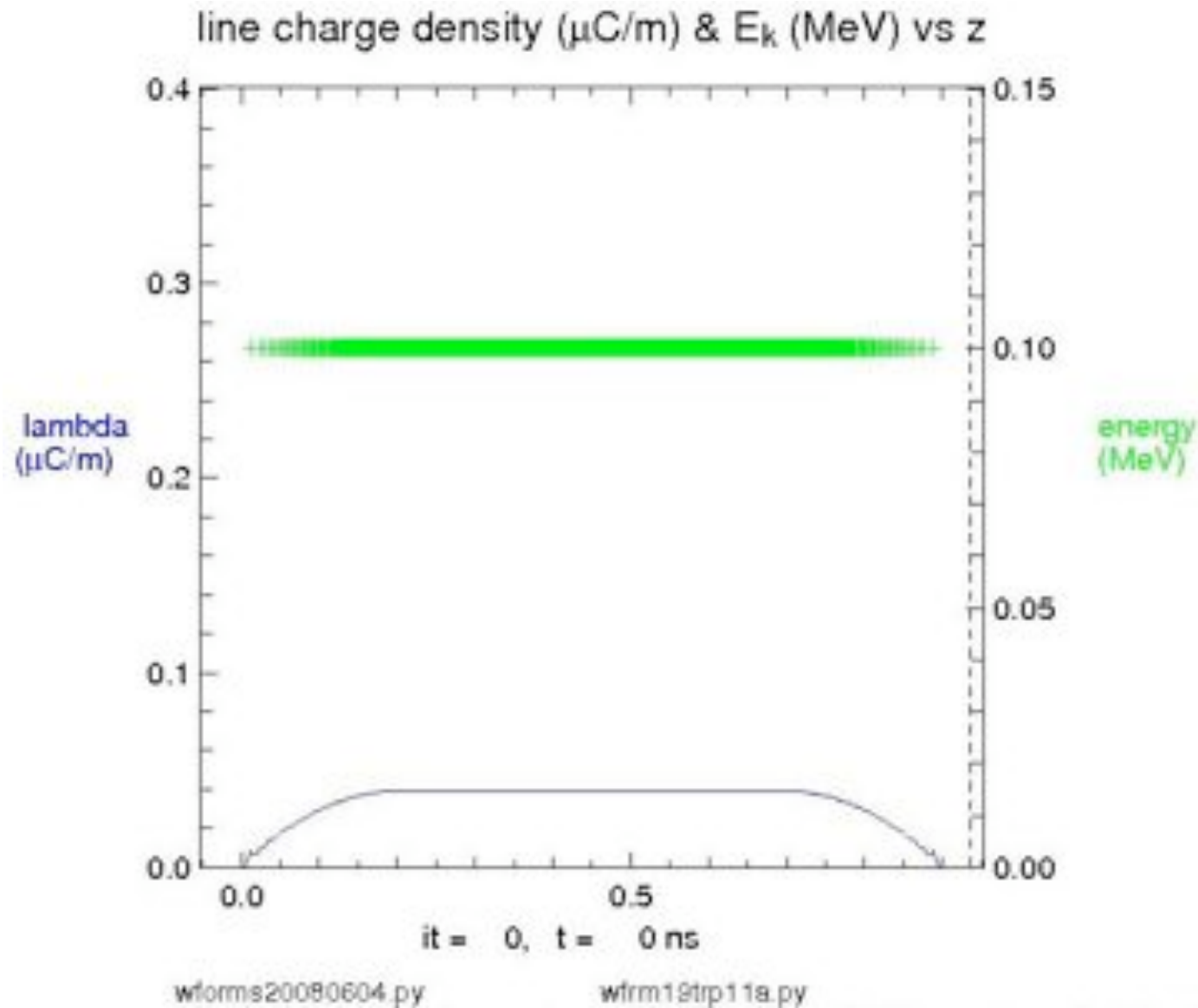
From 1-D code:



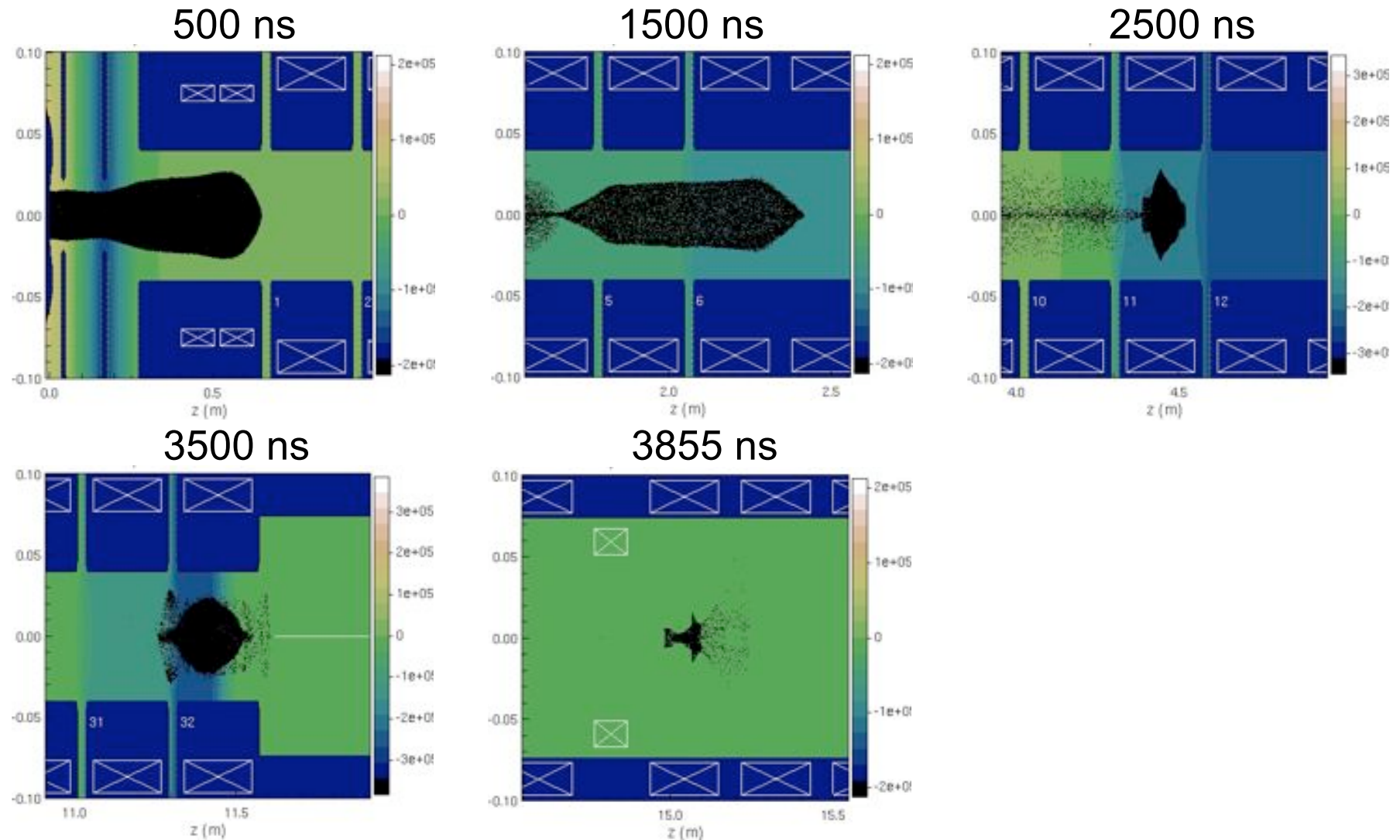
A series of snapshots shows how the (E_k, z) phase space and the line charge density evolve



Video: line charge density and kinetic energy profiles vs. time

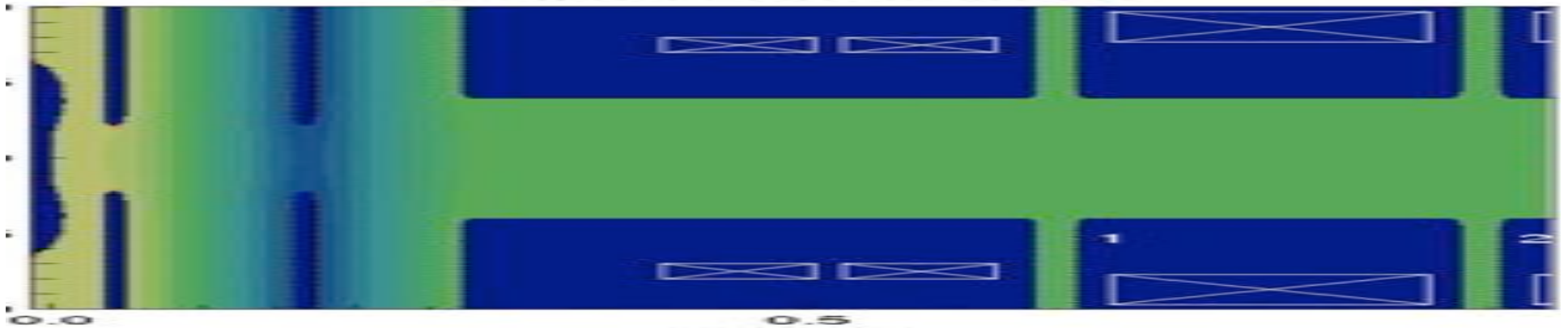


We use the Warp code to simulate the NDCX-II beam in (r,z)



Transverse confinement is satisfactory (some mismatch oscillations persist);
emittance growth (phase space dilution) is minimal

Video: Warp (r,z) simulation of NDCX-II beam



CONCLUDING REMARKS ...

- Fusion is a (potentially) attractive source of energy
... but hard to achieve
- Along the way: exciting science to study and technologies to develop
- Computer simulation plays a major role in Heavy Ion Fusion science research
- Kind of courses that are useful for a career in the area: Electromagnetics, Plasmas, Ordinary and Partial Differential Equations, etc.
- For more, visit the HIFS-VNL web site at <http://hif.lbl.gov>

BACKUP SLIDES

Motivation: energy and climate are coupled concerns

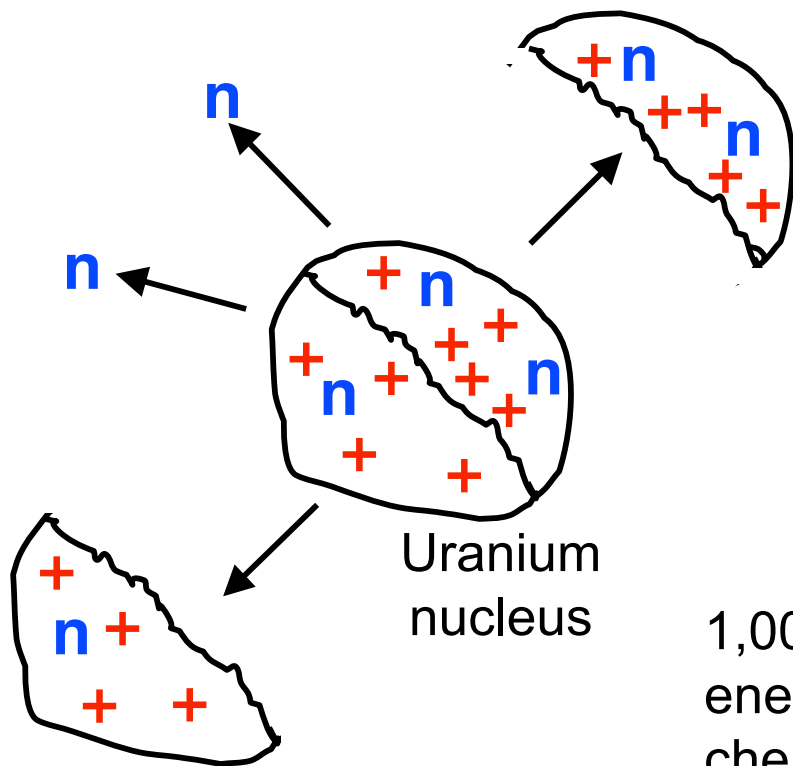
- Oil will be increasingly expensive
 - World oil production will peak in 0 - 30 years
 - Demand will increase due to:
 - population
 - increasing industrialization & standard of living in 3rd world
- Natural gas could last ~ 50-100 yrs, and coal 100's of years.

But ...

- Global warming, and air pollution, make reliance on coal problematic

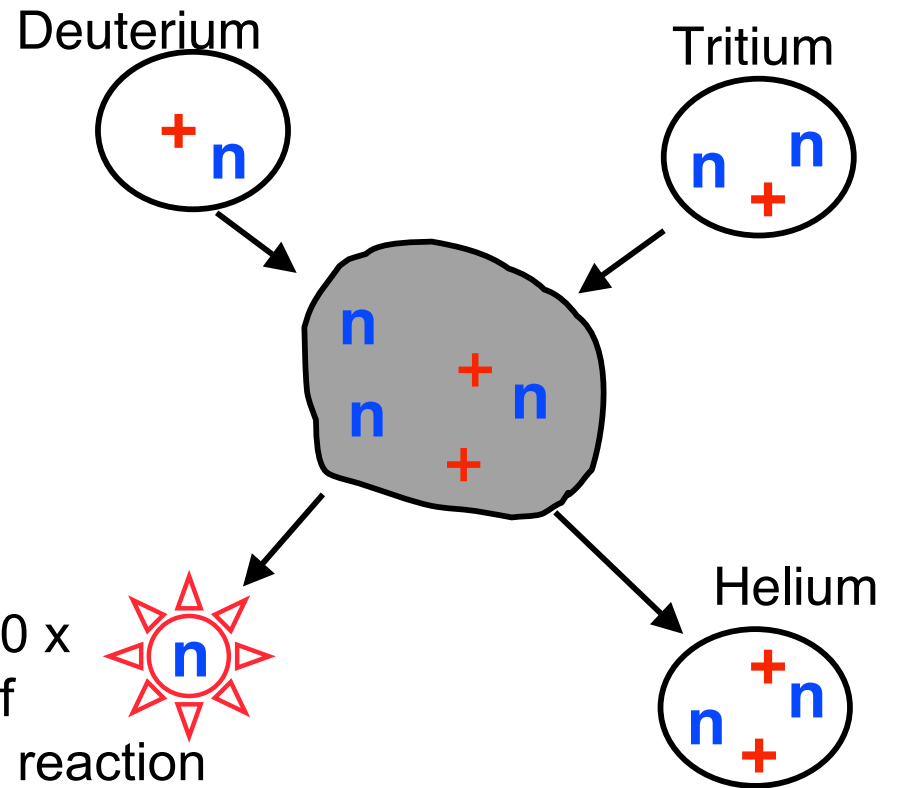
Fission and Fusion

Fission



Splitting a heavy atom
Nuclear power plants, A-bomb

Fusion



Combining light atoms
The sun & stars, H-bomb

Fusion reactions produce lots of energy

When D and T combine to make He, the nuclear force confines them

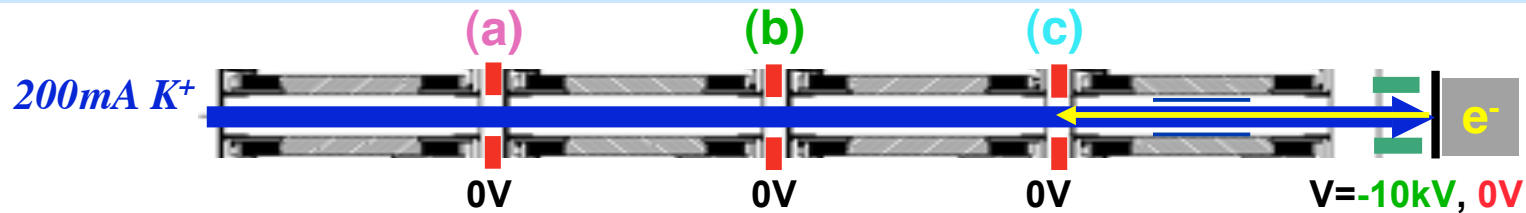
The new nucleus is in a lower energy state than D + T alone

Most of the extra energy is  given to the exiting neutron

$$(\text{Energy out}) / (\text{Energy in}) = 450$$

1 gallon of water = 300 gallons of gasoline
(only 0.015% of water is deuterium)

Comparison sim/exp: effects of electrons on beam



- The electron suppressor is turned **on** ($V = -10kV$) or **off** ($V = 0V$)

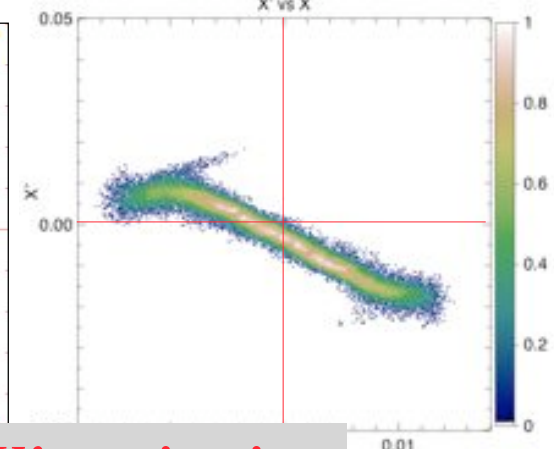
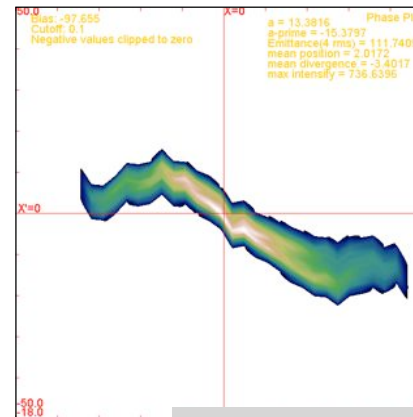
Suppressor **on**

- Exp./Sim. data agree semi-quantitatively.

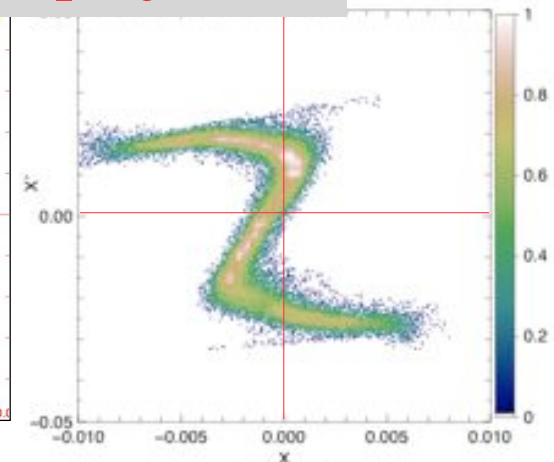
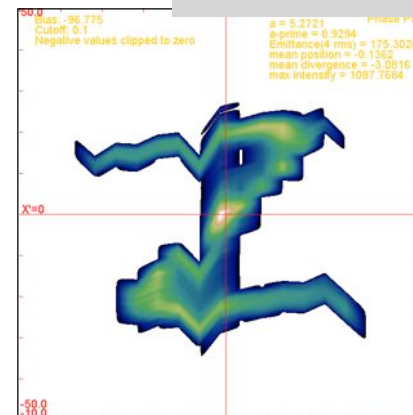
Suppressor **off**

experiment

simulation

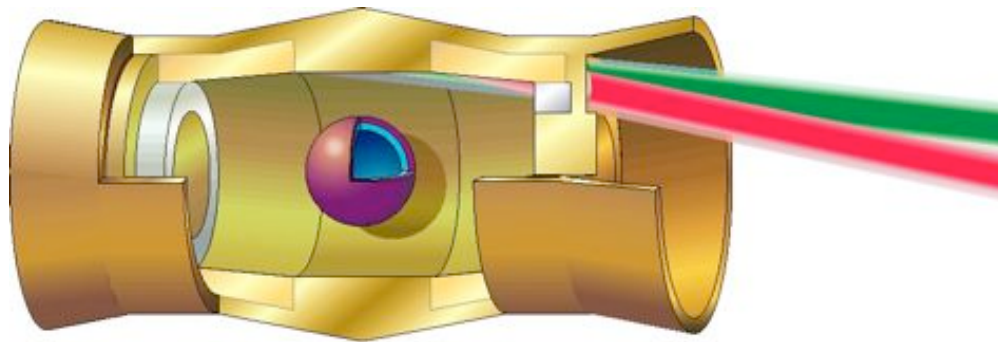


Beam XX' projection

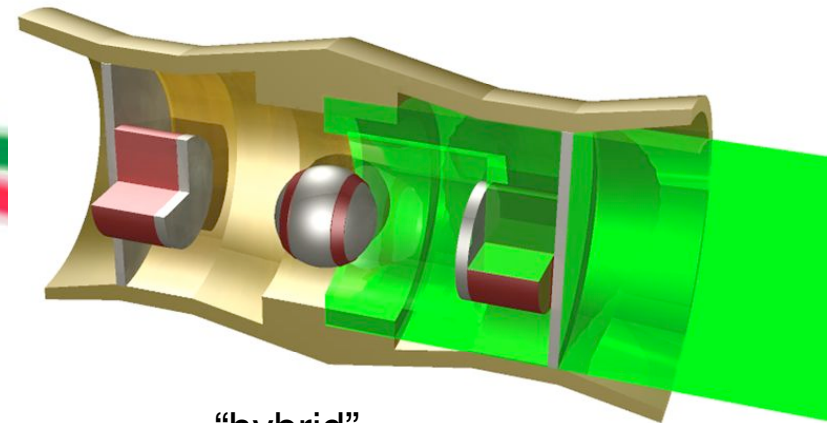


For symmetric illumination, the target is enclosed into a capsule

- Examples of capsule



“close coupled”

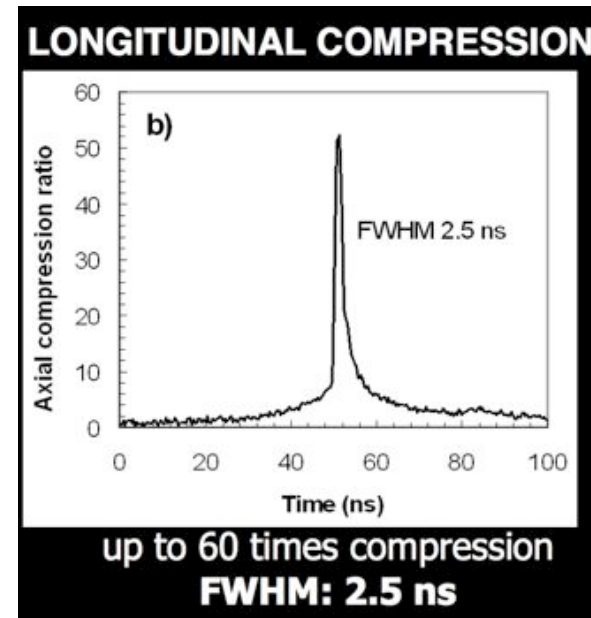
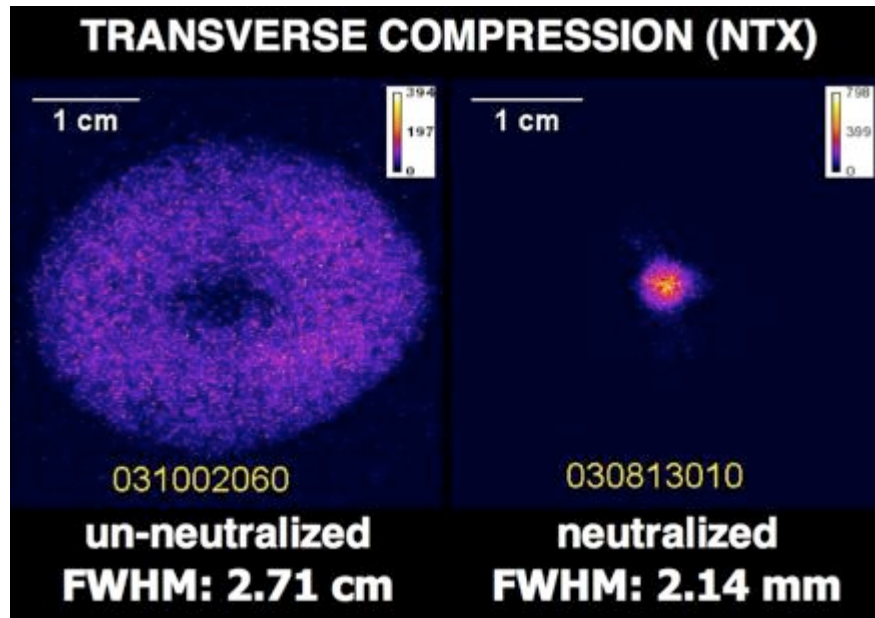


“hybrid”

- Hydrodynamic simulation of target implosion and capsule expansion



NDCX-I, and the earlier Neutralized Transport Experiment (NTX), showed that plasma can cancel a beam's space-charge repulsion



PRL 95, 234801 (2005)

PHYSICAL REVIEW LETTERS

week ending
2 DECEMBER 2005

Drift Compression of an Intense Neutralized Ion Beam

P. K. Roy,¹ S. S. Yu,¹ E. Henestroza,¹ A. Anders,¹ F. M. Bieniosek,¹ J. Coleman,¹ S. Eylon,¹ W. G. Greenway,¹ M. Leitner,¹
B. G. Logan,¹ W. L. Waldron,¹ D. R. Welch,² C. Thoma,² A. B. Sefkow,³ E. P. Gilson,³
P. C. Efthimion,³ and R. C. Davidson³

¹Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California, 94720, USA

²ATK Mission Research, Albuquerque, New Mexico 87110-3946, USA

³Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543-0451, USA

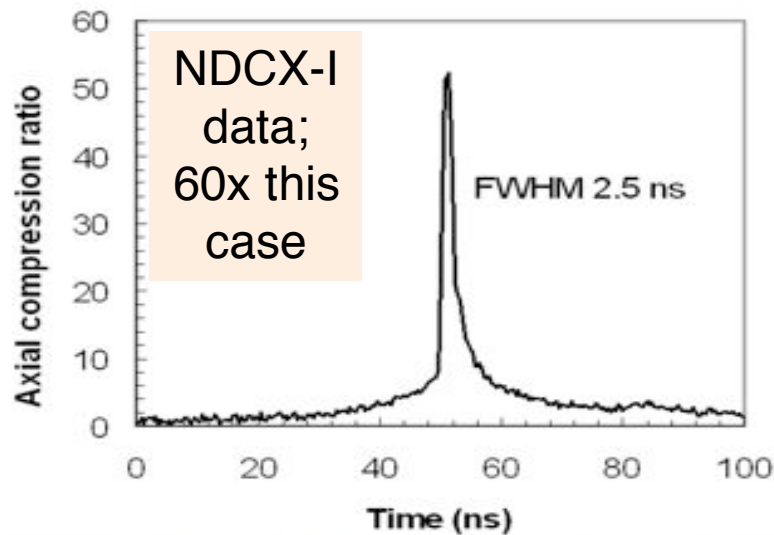
(Received 9 September 2005; published 29 November 2005)

Longitudinal compression of a velocity-tailored, intense neutralized K^+ beam at 300 keV, 25 mA has been demonstrated. The compression takes place in a 1–2 m drift section filled with plasma to provide space-charge neutralization. An induction cell produces a head-to-tail velocity ramp that longitudinally

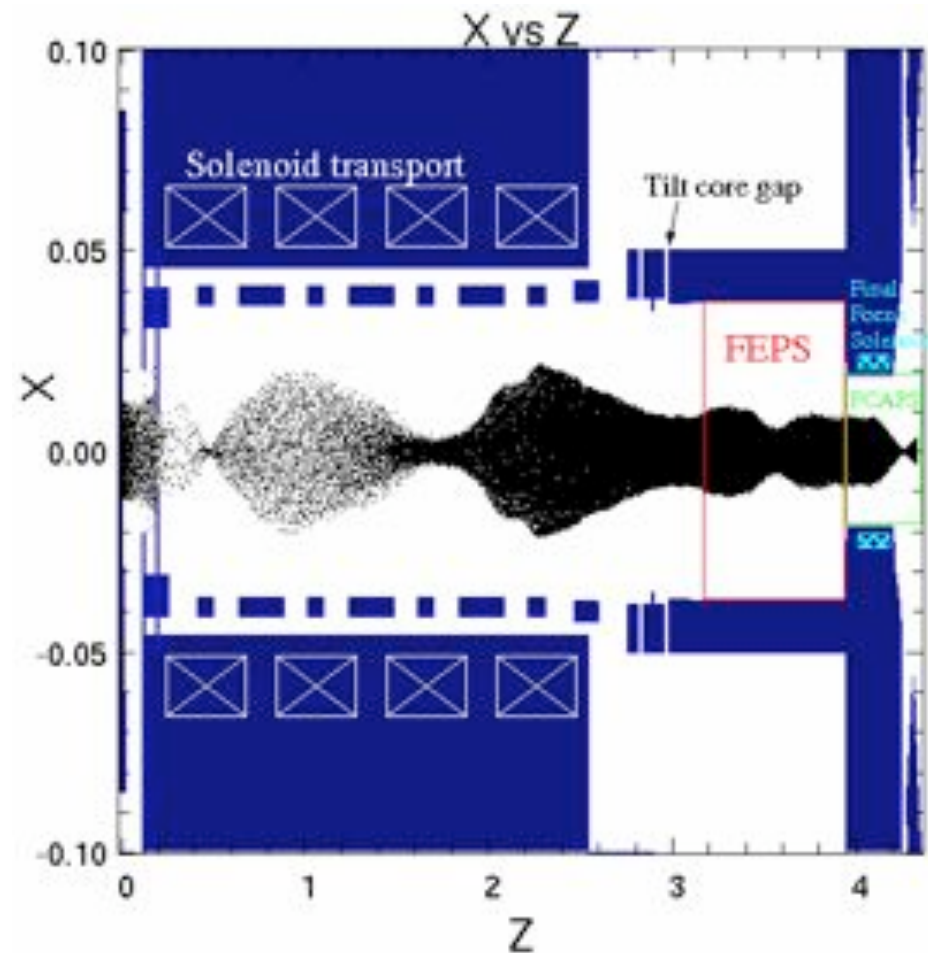
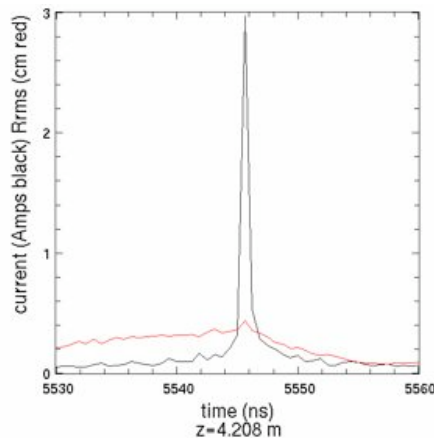
The Heavy Ion Fusion Science Virtual National Laboratory



Experimental data and simulations agree often, but not always (these are difficult problems)



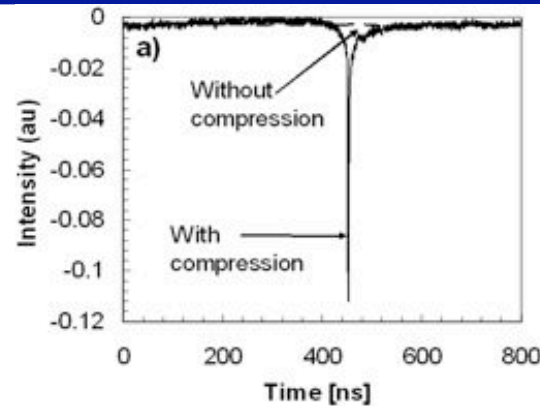
up to 60 times compression



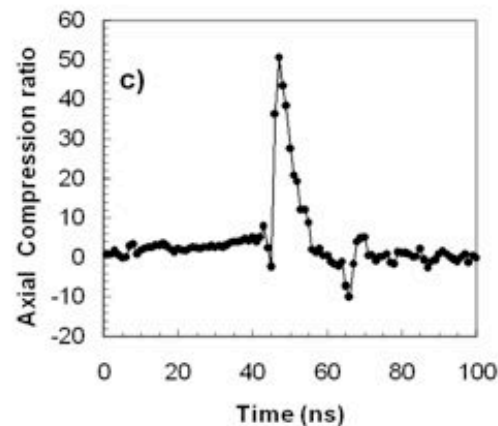
Here, a Warp result is shown; much work has used the LSP code

50-fold* compression measured

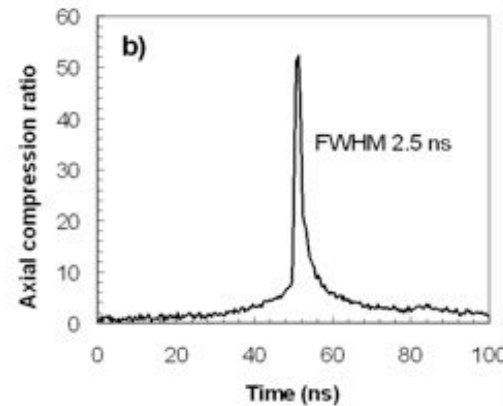
Phototube
signal
with & without
compression



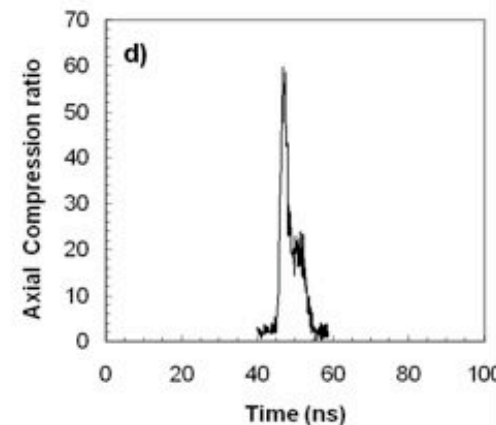
Compression
ratio
obtained using
Faraday cup



Compression
ratio
Obtained
using phototube



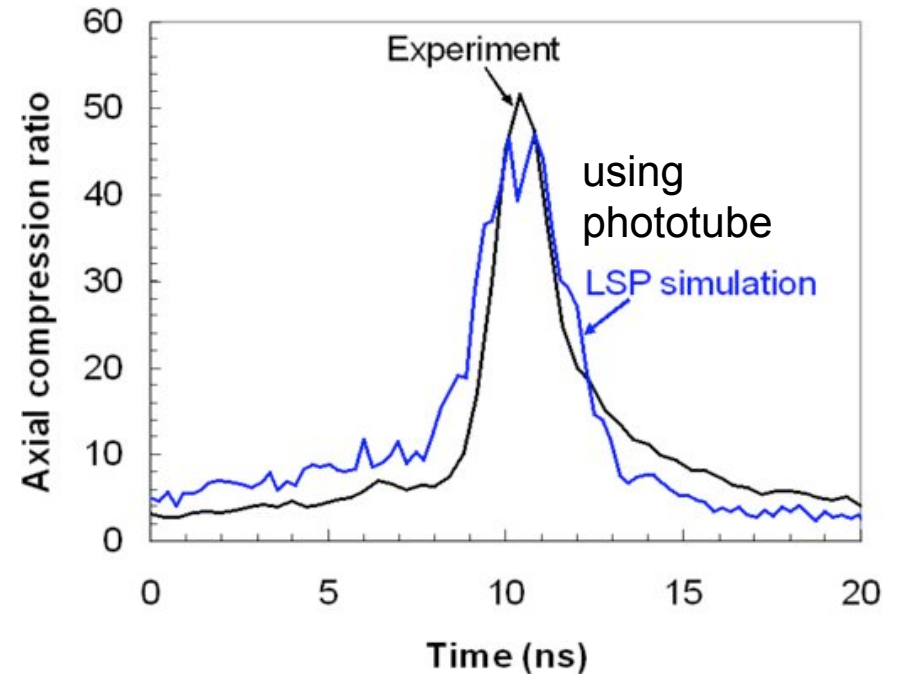
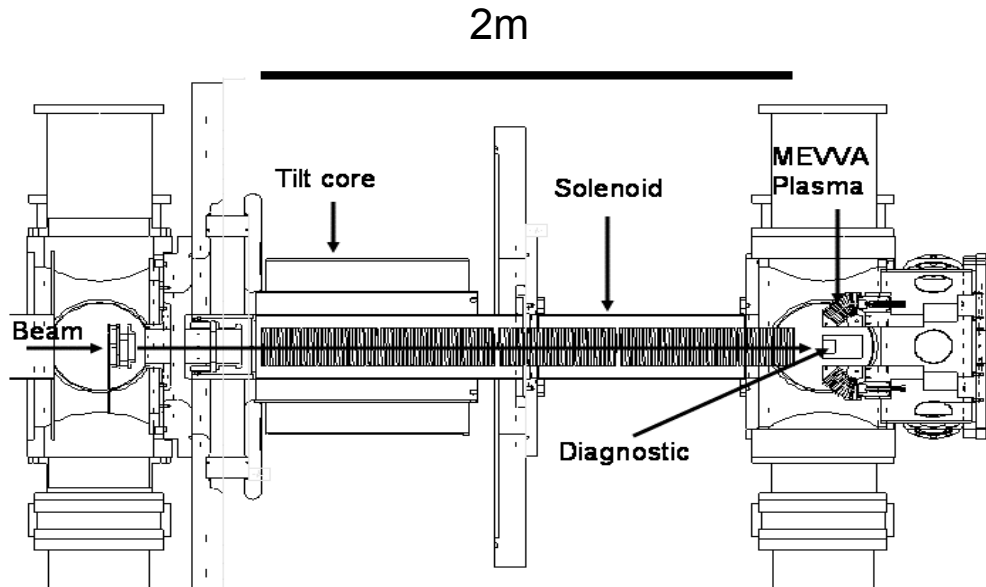
Compression
ratio
Obtained using
LSP simulation



The maximum compression is observed by fine tuning the beam energy to match the voltage waveform and precisely positioning the longitudinal focal point at the diagnostic location.

*Slightly different diagnostic and data reduction yield a factor of 60

Beam stability test with 2-m drift section



- As the drift length is increased, the compression is more sensitive to:
 - the degree of neutralization and
 - intrinsic longitudinal temperature.
- If there are any instabilities, e.g. two-stream, they may become evident with longer drift length.

- Longitudinal beam temperature: $\sim 1\text{eV}$

- No evidence of two-stream degradation or collective instabilities

NDCX-II target concept, and driver requirements for > 1 eV

ALUMINUM TARGET FOIL

Thickness (for $< 5\% \Delta T$):

~ 3.5 micron, solid density foil (range is 5 microns)

~ 35 micron, 10% solid density foam

LITHIUM ION BEAM BUNCH

Final Beam Energy: **2.8 MeV**

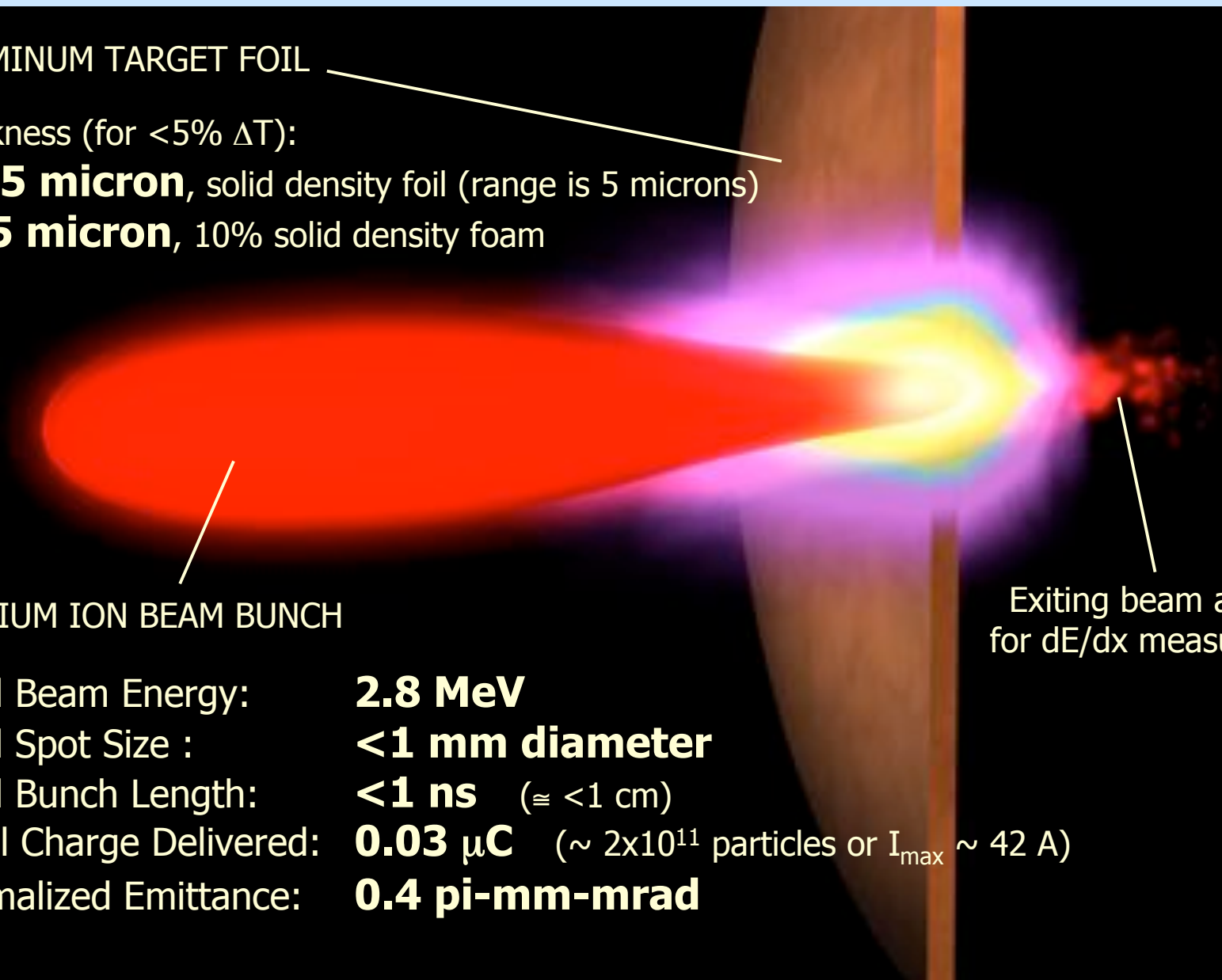
Final Spot Size : **< 1 mm diameter**

Final Bunch Length: **< 1 ns** ($\cong < 1$ cm)

Total Charge Delivered: **$0.03 \mu\text{C}$** ($\sim 2 \times 10^{11}$ particles or $I_{\text{max}} \sim 42$ A)

Normalized Emittance: **0.4 pi-mm-mrad**

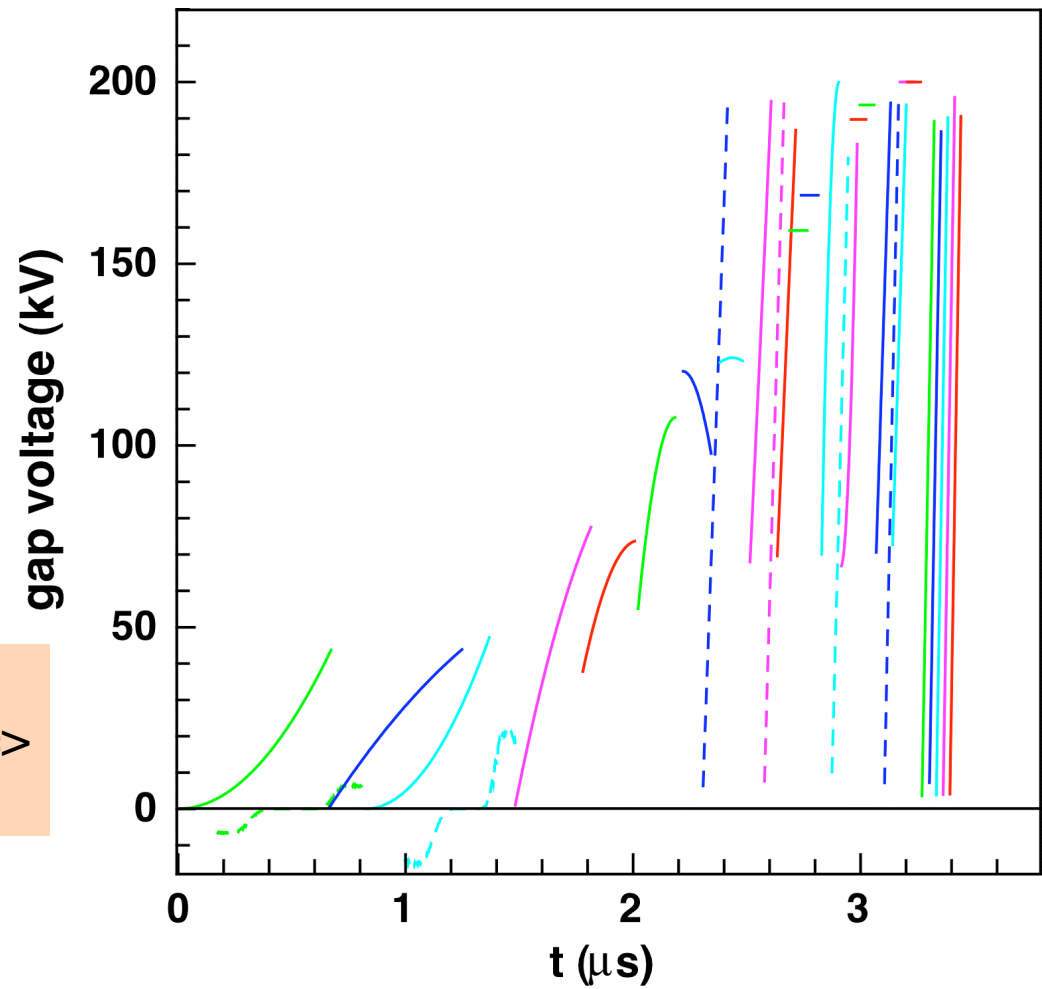
Exiting beam available
for dE/dx measurement



NDCX-II will make effective use of assets (accelerating cells and Blumleins) from decommissioned ATA accelerator

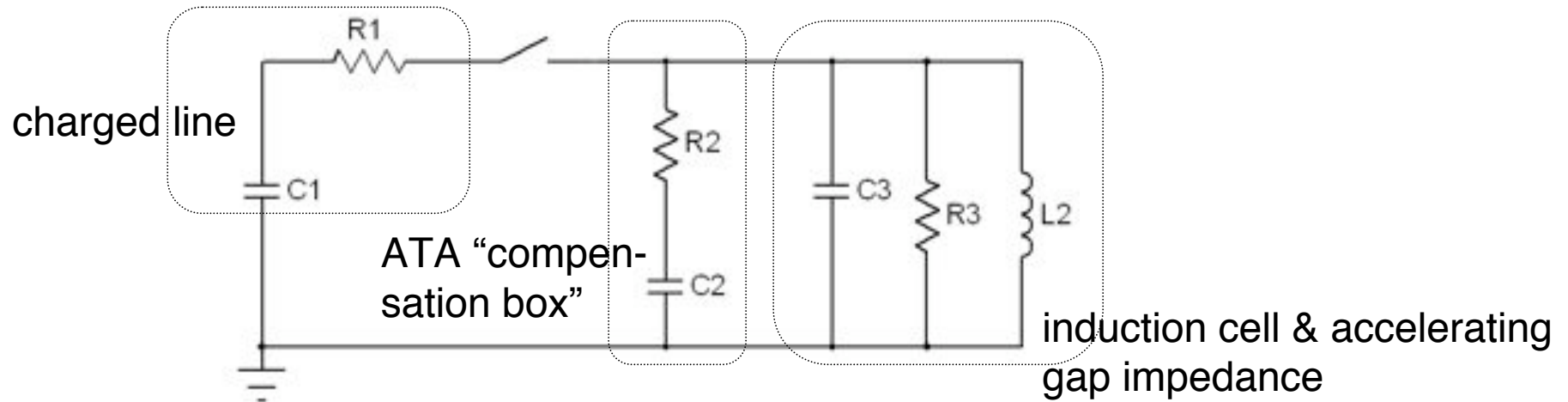
- 1-D optimizing code develops waveforms; “spotting scope” for Warp (r,z) runs
- The required waveforms are “simple” and can be generated via passive circuits
- Warp runs capture beam evolution in realistic self-consistent fields; output beam to feed into target simulations
- Need high longitudinal phase-space density; after neutralized drift compression, beam FWHM ~ 1 ns.

Typical set of 31 accelerating waveforms for Li beam
(yields 3.4 MeV, 30 nC) ==>

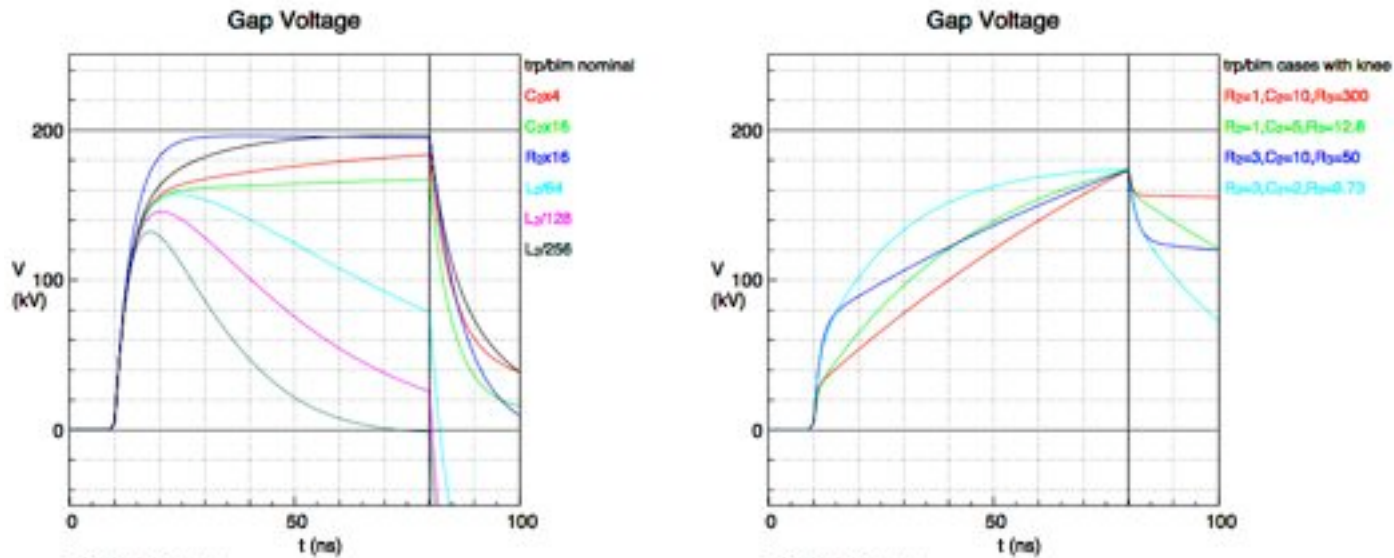


(For further information, contact Alex Friedman, Bill Sharp, or Will Waldron)

A simple passive circuit can generate a wide variety of waveforms



Waveforms generated for various component values:



NDCX-II represents a significant upgrade over NDCX-I

	Ion (atomic number / mass of common isotope)	Linac voltage - MV	Ion energy - MeV	Beam energy - J	Target pulse - ns	Range -microns (in ..)	Energy density 10^{11} J/m^3
NDCX-I	K^+ (19 / 39)	0.35	0.35	0.001-0.003	2-3	0.3/1.5 (in solid/20% Al)	0.04 to 0.06
NDCX-II	Li^{+1} (3 / 7) or Na^{+3} (11 / 23)	3.5 - 5	3.5 - 15	0.1 - 0.28	1-2 (or 5 w hydro)	7 - 4 (in solid Al)	0.25 to 1

- Baseline for WDM experiments: 1-ns Li^+ pulse ($\sim 2 \times 10^{11}$ ions, 30 nC, 30 A)
- For experiments relevant to ion direct drive: require a longer pulse with a “ramped” kinetic energy, or a double pulse.

The HIF program offers students a broad spectrum of opportunities for thesis research

- Particle beam physics
- Accelerator engineering
 - pulsed power
 - mechanical
- Warm Dense Matter physics
- IFE target physics
- Inertial Fusion engineering
 - target chamber
 - target fabrication
- Systems studies for IFE

- Experiments
 - Diagnostics
 - Simulation
 - Theory
- ... and mixtures of these

For more information ----
contact me at:

AFriedman@lbl.gov
510-486-5592